"THOU
THAT TEACHEST
ANOTHER
TEACHEST THOU NOT
THYSELF?"

HEATH'S
PEDAGOGICAL
LIBRARY

PLATE I.

Fig. 1

Fig. 2

Fig. 3

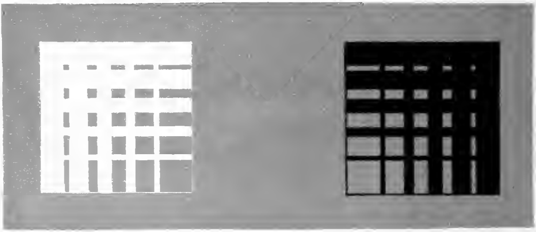


Fig. 4

A

COURSE

IN

EXPERIMENTAL PSYCHOLOGY

BY

EDMUND C. SANFORD, PH.D.

ASSISTANT PROFESSOR OF PSYCHOLOGY,
CLARK UNIVERSITY.

PART I: SENSATION AND PERCEPTION.

BOSTON, U.S.A.:
D. C. HEATH & CO., PUBLISHERS.
1896.

Typography by C. J. Peters & Son, Boston.

Presswork by S. J. Parkhill & Co., Boston.

PREFATORY NOTE

TO

EDITION OF ADVANCED SHEETS.

The portion of the course which follows will be found to treat of the senses only, and indeed not fully of them, for it still lacks a chapter upon some of the most interesting experiments in vision. The author's excuse for allowing the publication, even in this modest form, of so incomplete a work, must be the very extraordinary condition of experimental psychology at this time. Many laboratories have been opened, and many teachers of psychology are anxious to give their students the benefit of demonstrations and practice work, and yet there is absolutely no laboratory handbook of the subject to be had. At such a time half a loaf may be better than no bread — at least, so a number of the author's professional friends have seemed to believe; and, since the completion of the whole must be still further delayed, he offers this half loaf.

The course as planned consists of two parts: PART I on sensation and perception; and PART II on more complex mental phenomena.

PART I needs three chapters more to complete it: Chapter VII, on the Visual Perception of Extent, Distance, Direction, and Motion; Chapter VIII, On the Psychophysic Methods and Weber's Law; and Chapter IX, On Apparatus for the Study of the Senses. PART II will contain chapters on the following topics: Reflex and Voluntary

Movement, The Time Relations of Mental Phenomena, Association, Memory, Attention, and Emotion, so far as these subjects can be approached with experiments of moderate difficulty, together with a chapter on the apparatus necessary for such experiments.

E. C. S.

WORCESTER, *July*, 1894.

LABORATORY COURSE IN PSYCHOLOGY.

CHAPTER I.

The Dermal Senses.

The sense organs of the skin give us besides pain, tickling, shudder, and the like, the more special sensations of contact, heat, cold, and pressure. All these may be received passively when our members are at rest, or actively when our members are in motion, in which case special sensations of motion are blended with those just mentioned. We also assign to each sensation a more or less exact location. To examine some of these skin sensations is the purpose of this chapter.[1]

Sensations of Contact.

1. The Location of Touches. Touch yourself in several places with the same object, and analyze out, as far as you can, the particular quality of the sensation by which you recognize the place touched. This quality of a sensation is known as its "Local Sign."

Lotze,[2] *A*, 328 ff., 405 ff.; *B*, 39 ff. Stumpf.

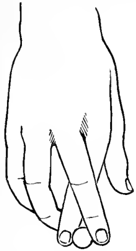
---

[1] As a general term for perceptions of touch in the widest sense, Max Dessoir (p. 242) suggests *Haptics* as an analogue of Optics and Acoustics. This he further divides into *Contact-sense* (including *a*, pure contact, and *b*, pressure) and *Psela-phesia*, from ψηλάφησις, touching, handling (including *a*, active touch, and *b*, "muscle sense").

[2] For full titles of books and articles referred to, see the bibliography at the end of the chapter. When several articles from one author are given, they have been lettered *A*, *B*, *C*, etc., and the references marked accordingly.

2. Location of Touches. Cause the subject to close his eyes; touch him on the fore-arm with a pencil point; and require him to touch the same point with another pencil immediately afterward. Estimate the error in millimetres and average the results for a number of trials, noting the direction of error, if it is constant. The subject must be allowed to correct his placing of the pencil if not satisfied with it on first contact.

3. Aristotle's Experiment. Cross the middle finger over the first in such a way as to bring the tip of the middle finger on the thumb side of the first finger. Insert between the two a pea or other small object. A more or less distinct sensation of *two* objects will result, especially when the fingers are moved. Some experimenters may find the illusion more marked when the pea is rolled about on the surface of the table with the crossed fingers, or when the third and little fingers are used instead of the first and middle fingers.



Aristotle, Hoppe, James, II., 86–87.

4. Eccentric Projection of Touches. Close the eyes, and tap with the tip of a cane on the floor, or, better still, on the walls and floor near a corner of the room. Notice that the origin of the sensations seems to be the tip of the cane and not the fingers or the arm. Attention to these parts, however, will show the true place of origin. If the cane is held rigidly at the lower end, there is little or no tendency to shift the sensations from the fingers and arm, unless the cane is limber. The eccentric projection of touches is only a special case of their location, and follows the same general laws. See also Ex. 41.

Weber, 483 f.; James, II., 31–43, 195–197; Dessoir, 219–232.

5. Judgments of Motion on the Skin. *a.* Let the subject close his eyes. Rest a pencil point or the head of a pin gently on his fore-arm and move it slowly and evenly up or down the arm. Require him to indicate his earliest judgment of the direction. If the experiment is carefully made, the fact of motion will be perceived before its direction.

b. Try a number of times, estimating the distances traversed in millimetres and averaging for the two directions separately. It will probably be found that the downward distances have been greater than the upward.

c. Starting from a fixed point on the fore-arm, move the pencil in irregular order up, down, right, or left, and require the subject to announce the direction of motion as before. Compare the results found with those found in Ex. 7.

Hall and Donaldson.

6. Feelings of Double Contact. *a.* If two parts of the body of like temperature are brought in contact, the two sensations do not blend, but the part that moves feels the one that does not; i. e., the sensations received by the moving part generally get more attention and are externalized. Try with the tips of the thumbs or fingers in contact. This general rule, however, has exceptions. Feel of the palm of the right hand first with the ball of the left thumb (which gives results in accord with the rule), then with the knuckle of the same thumb sharply bent. Light tapping of the forehead with the finger we feel in the forehead more markedly than in the finger, though usually with the hand on the forehead we feel the forehead.

b. If the parts are not of like temperature that which varies most from the normal bodily temperature will be felt by the other. Warm the right hand by holding it closed for a minute or two and then apply it to the forehead. The higher temperature will be perceived by the forehead, while

at the same time the hand as the more expert touch organ will perceive the form of the forehead. Cool the right hand by holding it a few minutes in cold water, dry it and apply it to the back of the left hand. The right hand may seem to be feeling of a cold left hand. In this case of course both the temperature and form feelings are credited to the right hand. If the temperature is not very different the direction of attention may dictate which shall be felt by the other.

Weber, 556–559; Dessoir, 229.

7. Weber's Sensory Circles. *a.* Find the least distance apart at which the points of the æsthesiometric compasses[1] can be recognized as two when applied to the skin of the fore-arm. Try also the upper arm, the back of the hand, the forehead, the finger-tip, and the tip of the tongue. Be very careful to put both points on the skin at the same time and to bear on equally with both. Cf. Weber's measurements as given in the text-books; also Goldscheider's (quoted by Ladd, p. 411).

b. Compare the distance between the points just recognizable as two when applied lengthwise of the arm with that found when they are applied crosswise. Compare the results found in *a* and *b* with those found in Ex. 5, but remember that this compass experiment requires the discrimination of the points.

c. Give the points a slightly less separation than that found for the fore-arm crosswise, and beginning at the elbow draw the points downward side by side along the arm. They will at first appear as one, later as two, after which they will appear to separate as they descend. Something similar will be found on drawing the points from side

---

[1] For the apparatus needed in this and later experiments, see the list and descriptions in the chapter on apparatus below.

to side across the face so that one shall go above, the other below the mouth.

d. Make the skin anæsthetic with an ether spray and test the discriminative sensibility as before.

Weber, 524–530, 536–541; Goldscheider, *B*, 70 ff., 84 ff.

8. Filled Space is relatively under-estimated on the skin. Set up in a small wooden rod a row of five pins separated by intervals of half an inch, and in another two pins two inches apart. Apply to the arm like the compasses above. The space occupied by the five pins will seem less than that between the two. A still simpler way given by James is as follows: Cut one end of a visiting card into a series of notches, and the other into one long notch so as to leave two points as far apart as the outer points at the other end, but separated by an empty interval. Apply to the skin as before. This illusion, though very clear for some experimenters, does not seem equally so for all, and some have difficulty with it.

James, II., 141, footnote.

9. Active Touch is far more discriminating than mere contact. Compare the sensations received from simply resting the tip of the finger on a rough covered book with those received when the finger is moved and the surface "felt of."

10. The Time Discriminations of the sense of contact are very delicate. Strike a tuning-fork; touch it lightly, and after about a second remove the finger so as not to stop the fork. The taps of the fork on the skin do not blend into a smooth sensation even when the vibrations are several hundred a second. One may assure himself that the touching does not much alter the rate of the fork by using another that beats with the first. If the touching is carefully done,

the rate of the beats will not be noticeably altered. (On beating forks see Chap. IV.) The roughness may also be felt but not so strongly, by setting the stem of the fork upon the skin. The roughness of the pulses of air from large tuning-forks can also be felt when the hand is brought near, but not into actual contact with them.

Wittich, 335 ff.; Schwaner; Sergi.

11. After-images of Touch. Touch the skin of the wrist lightly with the point of a needle, and notice that beside the original sensation, there is, after a more or less free interval, a second pulse of sensation. The interval is brief, a second or under, and the sensation appears to come from within. In quality it is like the first, but without the pressure component. The prick of the needle point is not essential; the second sensation can be observed when the head of a pin is applied. Too hard touches must be avoided in testing for these images, as they give rise to a continuous after-image that fills the interval. The second image is apparently due to a double conduction in the spinal cord, and is therefore different from the after-images of the other senses. A portion of the original excitation is conveyed in the posterior columns of the cord to the cortex. Another portion goes by a slower path through the central gray matter of the cord. Cf. Ex. 32.

Goldscheider, *II*, 168 f.

12. An Interesting Illusion of Length, based on the time during which a touch sensation continues, may be observed as follows: Require the subject to close his eyes. Take a piece of coarse thread a couple of feet long and make a knot in the middle of it. Place the knot between the thumb and forefinger of the subject, asking him to press it gently. Then draw the thread slowly through between his thumb and finger and ask him to estimate its length. Repeat the

process, this time drawing it rapidly. The drawing must not be too slow in the first case nor too fast in the second, or the nature of the illusion may be suggested to the subject and more or less completely corrected.

Loeb, 121–122.

For Minimal Contact in relation to Pressure, see Ex. 22; in relation to Tickle, see Ex. 31.

Sensations of Temperature.

13. Hot and Cold Spots. *a.* Move one of the pointed brass rods, or even a cool lead-pencil, slowly and lightly over the skin of the back of the hand. At certain points distinct sensations of cold will flash out, while at others no temperature sensation will be perceived, or, at most, only faint and diffuse ones. Heat one of the rods slightly in the gas flame and repeat the experiment. More care will be required in locating the hot spots than the cold spots, for their sensations seem less distinct.

b. On some convenient portion of the skin mark off the corners of a square 2 cm. on the side. Go over this square carefully both lengthwise and crosswise for both heat and cold, drawing the point along lines 1mm. apart, and note on a corresponding square of millimetre paper the hot and cold spots found, hot spots with red ink, cold with black. This time the points should be heated or cooled considerably by placing them in vessels of hot or cold water, and should be kept at an approximately constant temperature by frequent change, one being left in the water while the other is in use. Break the experiment into a number of sittings so as to avoid fatiguing the spots, for they are very easily fatigued. A map made in this way cannot hope to represent all the spots, but it will suffice to show the permanence of some of them and possibly to show a little their general arrangement. When the map has been made, select a responsive

and isolated cold spot, and try it with a warm point. Try a similar hot spot with a cold point.

c. Notice the very distinct persistence of the sensations after the point has been removed, that is, the temperature after-images.

An interesting question suggested by this punctual location of temperature sensations is this, namely: How does it come about that we ordinarily conceive such sensations as continuous over considerable areas.

Blix; Goldscheider, *A*, *B*, *E*; Donaldson.

14. Mechanical and Chemical Stimulation of the Temperature Spots.[1] The temperature spots respond with their characteristic sensations to mechanical and chemical stimulation (and some observers find also, to electrical stimulation), and do not give pain when punctured.

a. Choose a very certainly located cold spot and tap it gently with a fine wooden point (not too soon after locating it, if it has been fatigued in locating); or better, have an assistant tap it. Thrust a needle into a well-located cold point. Try both for comparison on an adjacent portion of the skin.

b. Choose a convenient area, say, on the back of the hand or the temple, and rub the skin lightly with a menthol pencil. After a little the sensation of cold will appear. Goldscheider's tests with a thermometer applied to the skin show that the sensation is not due to an actual cooling of it. The menthol makes the nerves of cold at first hyperæsthetic (so that they respond with their specific sensation to

[1] Such experiments as these illustrate the Law of the Specific Energy of Nerves, which may be stated somewhat as follows: Every stimulus that can excite a sensory nerve at all, causes such sensations as follow the stimulation of that nerve in its customary way and only such. As regards the interpretation to be put on the phenomena thus generalized there is dispute. Goldscheider *I*; Wundt, 3te Aufl. I. 332 ff., 4te I. Aufl. 323; Helmholtz, Sensations of Tone, 148; Optik, 2te Aufl. 233, 1te Aufl. 193; Ladd, 307, 353.

mere contact, and give an intenser sensation when a cold body is applied than do adjacent normal portions of the skin); afterward, however, all the cutaneous nerves become more or less anæsthetic.

c. Chemical stimulation of the heat nerves can be tested with CO_2. Provide two like vessels; place them side by side and fill one with CO_2. Plunge the hand into the vessel containing the gas, and for comparison into the one containing air. For the additional experiments necessary to prove this to be a real chemical stimulation, see the literature.

Blix, Goldscheider *A*, *B*, *D*, *F*, and Donaldson; on *c*, R. Du Bois-Reymond.

15. The Temperature of the Skin at any moment is a balance between its gain and loss of heat. Anything that disturbs that balance, causing increased gain or loss, produces temperature sensations. It is common experience that a piece of cloth, a bit of wood, a piece of metal, all of the same temperature as the air that seems indifferent to the hand, cause different degrees of the sensation of cold when touched, because they increase the loss of heat by conduction in different degrees. If a paper bag be placed over the hand held upward, a sensation of warmth is soon felt, because of the decreased loss of heat.

16. The Shifting of the "Physiological Zero." *a.* Provide three vessels of water, one at 30° C., the second at 40°, the third at 20°. Put a finger of one hand into the warmer water, a finger of the other into the cooler. At first the usual temperature sensations will be felt, but after a little they disappear more or less completely, because of the fatigue of the corresponding temperature organs. Now transfer both fingers to the water of normal temperature. It will seem cool to the finger from warmer water and warm to the one from cooler. This experiment has been sometimes regarded as one of successive contrast.

b. Hold the hand for one minute in water at 12° C., then transfer it to water at 18°. The latter will at first feel warm, but after a time cold again. The water at 18° first causes a decrease in the loss of heat or a slight gain. but later a continued loss.

Weber; Hering; Goldscheider, *B*, 32 ff.

17. Effect of Extent of Surface Stimulated. The intensity of the sensation increases as the stimulated area increases. Dip the right forefinger (or hand) into hot or cold water, observe the sensation, and immediately insert the other forefinger to an equal depth. Vary the experiment by inserting the left finger first, and by inserting both at once and then withdrawing one. The original experiment of Weber, who inserted first a finger, and then the whole of the other hand, gives striking results, but has the fault, as Goldscheider rightly observes, of adding a more sensitive as well as a larger area. This experiment must not be inconsiderately contrasted with Ex. 23.

Weber, 553; Goldscheider, *G*, 475–476.

18. Temperature Fatigue. *a.* Extreme temperatures fatigue the sensory apparatus of both heat and cold. Hold a finger in water at 45° C., the corresponding finger of the other hand in water which feels neither cold nor hot (about 32°). After 30 seconds dip them alternately into water at 10°. The finger from the water at 32° will feel the cold more strongly. Hold a finger in water at 10°, the corresponding finger of the other hand in water at 32°. After 30 seconds dip them alternately in water at 45°. The finger from the water at 32° will feel the heat more strongly.

b. The fatigue of the temperature apparatus may produce an apparent contradiction of Ex. 17. Plunge one hand entirely under cold water and keep it there for a moment. Then dip the finger of the other hand or the whole hand

several times in the same water, withdrawing it immediately each time. The water seems colder to the finger or hand which is only dipped.

Weber, 570; Goldscheider, *B*, 34 ff.

19. Temperature After-images. *a.* Hold a cold piece of metal on the forehead or on the palm of the hand for half a minute. On removing it the sensation of cold continues, though the actual temperature of the skin is rising. Sometimes fluctuations are observed in the persisting sensation. After contact with a hot body the sensation of heat continues in the same way, though the temperature of the skin falls. Goldscheider explains this result for cold in part by the persistence of the cold sensation in the manner of an after-image, and in part by the lessened sensibility of the nerves of heat; a similar explanation *mutatis mutandis* holds also for heat.

b. Intermittent after-images, or those that recur after an interval more or less free of sensation, have been observed especially with repeated stimulation. Heat a key till it is just a little short of painfully hot, touch some part of the skin, e.g., the wrist, three or four times at intervals of about half a second. The after-image of the heat will appear several seconds later. Try the same for cold, but use a key that is at the temperature of the air.

Cf. Ex. 13 *c.*, also the after-images of hearing and vision, Chapters IV. and V., and notice that all the temperature after-images are positive; i.e., like the original sensation.

Goldscheider, *B*, 11, 34 ff., 38; on *b*, Dessoir, 300.

20. Fineness of Temperature Discrimination. *a.* Find what is the least perceptible difference in temperature between two vessels of water at about 30° C., at about 0°, and about 55°. The finest discrimination will probably be found with the first mentioned, if the discrimination does

not prove too fine at all these points to be measured with the thermometers at hand. Use the same hand for these tests, always dipping it to the same depth. It is better to dip the hand repeatedly than to keep it in the water.

b. The different surfaces of the body vary much in their sensitiveness to temperature. The mucous surfaces are quite obtuse. When drinking a comfortably hot cup of coffee, dip the upper lip into it so that the coffee touches the skin above the red part of the lip, or dip the finger into it; it will seem burning hot. Plunge the hand into water at 5–10° C. The sensation of cold will be strongest at first on the back of the hand where the skin is thin, but a little later will come out more strongly in the palm, where it will continue to be stronger and may finally approach pain.

c. The middle line of the body is less sensitive to temperature than portions at either side of it. Touch the middle of the forehead, or the tip of the nose, with a piece of warm or cold metal and then touch several places to the right and left of that point.

Fechner; Weber, 552 ff.; Goldscheider, *B*, 49 ff.

SENSATIONS OF PRESSURE.

21. Pressure Points. Make an obtuse but extremely fine cork point (pyramidal in shape; for example, the pyramid a quarter of an inch square on the base and of equal height), set it upon the point of a pen or other convenient holder, or use a match whittled down to a fine point, or even a needle. Choose an area on the fore-arm and test for its pressure spots somewhat as for the hot and cold spots, but this time set the cork point as lightly as possible on point after point of the skin instead of drawing it along. Two kinds of sensation will be felt; at some points a clear feeling of contact with a sharp point will be felt, at others no feeling at all, or

a dull and vacuous one. The first are the pressure points. Goldscheider describes their sensations on light contact as "delicate," "lively," "somewhat tickling . . . as from moving a hair;" on stronger pressure, "as if there were a resistance at that point in the skin, which worked against the pressure stimulus;" "as if a small hard kernel lay there and was pressed down into the skin."

The first are said to be more sensitive to small changes of pressure, and though with sufficient increase both give pain, their sensations retain their characteristics. They are closer together than the temperature spots, and harder to locate. The fact that our most frequent sensations of pressure are from surfaces and not from points is perhaps the reason it is difficult at first to recognize a pressure quality in these sensations.

Goldscheider, *B*, 76 ff.

22. Minimal Pressure or Simple Contact. Find weights that are just perceivable on the volar side of the fore-arm and on the tips of the fingers. Try also, if convenient, the temples, forehead, and eyelids. In applying the weights, see that they are brought down slowly upon the surface of the skin, that they touch equally at all points, and that their presence is not betrayed by motion of the weight after it touches the skin. This can be done by using a penholder or small rod, with its tip put through the ring of the weight, for laying it on. Compare the relative sensibility found by this method with that found with Weber's compasses for the same parts (Ex. 7) and note that the latter requires discrimination, not mere perception. See also Exs. 29 and 31.

Aubert and Kammler; Bloch.

23. Relation of Apparent Weight to Area of Surface Stimulated. Test with the equal weights of unequal size

upon the hand, properly supported to exclude "muscle sense." The smaller will seem decidedly heavier.

24. Discriminative Sensibility for Pressures. Use the pressure balance if one is at hand; if not, have the subject close his eyes and lay his hand, palm upward, on such a support as will bring his arm into a comfortable position and make his palm level; for example, on a folded towel placed on a low table or the seat of a chair. (The matter of an easy position for the subject is of cardinal importance in all psychological experiments.) The method of experimenting here to be used is that of the "Just Observable Difference" or "Minimal Change;" it may be applied as follows: Lay in the subject's palm a piece of thick and soft blotting-paper just large enough to prevent the weight from touching the skin. Place the standard weight of 100 grams upon the paper and allow it to remain a sufficient time for the subject to get a clear perception of its weight. Then remove it and immediately put in its place a weight of 110 grams, allowing that to remain as long as the first. If the subject can recognize this difference easily and surely, try him with 109, 108, and so on, alternating the standard weight and a weight to be compared with it till a weight is found that is just recognizably different from the standard. If 110 grams is not recognizably different, take 111, 112 instead of 109, 108. Occasionally follow the standard with another 100 gram weight to guard against illusion on the part of the subject. After having determined the just observably greater weight, find the one that is just observably lighter in the same way. Make a good number of determinations of these just observably heavier and lighter weights, sometimes going toward the standard and sometimes away from it. Take the differences between them and the standard weight and average the results. The ratio of this average to the standard will be a measure of the dis-

criminative sensibility required. If, for example, the ratio for one subject is 7 : 100 and for another 14 : 100, the first has a sensibility to pressure differences twice as acute as the second. In half of the tests, both above and below, the standard weight must be placed upon the hand first, and in half the weight to be compared with it. It is well also to distribute the determinations of the differences above and below so that they shall be about equally affected by practice and fatigue. The aim should always be to keep all the conditions of the experiment as constant as possible and especially to have them the same for the weights to be compared. Be careful in putting on the weights that the subject does not recognize a difference in the force with which they strike; also that suggestions by difference of temperature or by sounds made in selecting the weights are avoided.

It is easy to see that this method has some disadvantages. First, it leaves to the feeling of the subject what the just observable difference is, and this feeling is liable to change from subject to subject and in the same subject at different times. In using this method the subject must know the direction of the change that he is to recognize, and so is somewhat exposed to the influence of expectant attention. And finally, when weights are found that are just observably different, it is possible that they are a little larger than the subject could just recognize; that is, that he has allowed himself a small margin for security. These difficulties may be partially obviated by a more rigorous application of the method.

Thus in making the tests for the just observable differences above and below, weights must first be taken that are not recognizably different from the standard, and must then be slowly increased or decreased till just observably different. Subjective equality must be regarded rather than objective

equality, if the two are at odds, as sometimes happens. To these tests two others must be added; namely, for the just *un*observable differences above and below, the operator now selecting a weight that is clearly heavier than the standard and decreasing it gradually till it can just no longer be recognized as different, and similarly selecting one that is at first clearly lighter than the standard and increasing it till it seems the same. The average of the four tests, just recognizably different and just *un*recognizably different, is then taken for the ratio. When great accuracy is required the method must be used in this complete form. For other methods and fuller literature, see the chapter on Weber's Law below.

Weber, 543–549; Wundt, 3te Aufl., I., 343 ff., 350; 4te Aufl., I., 336 f., 341 ff.

25. Temperature and Pressure. Cold and hot bodies feel heavier than bodies of equal weight at a normal temperature.

a. For cold, take two dollar pieces, warm one until it ceases to seem cold; cool the other to 10° C. Apply alternately to the palm of the hand, letting the hand rest, meanwhile, on the table or some other support so as to exclude "muscle sense." The cold one will seem much heavier, perhaps as heavy as two at the normal temperature. The same experiment may be tried on the forehead with the head supported.

b. For heat take two wooden cylinders of equal weight; heat one to a high temperature by standing it on end in a metal vessel floating in a water bath. Apply the cylinders on end alternately to the back of the hand (supported) between the metacarpal bones of the thumb and first finger. The hot one will seem heavier.

Weber, 512, 551; Szabadfoeldi; Funke, 320; Dessoir, 304–306.

26. Pressure Evenly Distributed over a Considerable Area is less strongly felt than pressure upon an area bordered by

one that is not pressed. Dip the hand up to the wrist into water (or, better still, into mercury) of normal temperature, and notice that the sensation of pressure is strongest in a ring about the wrist at the surface of the water; possibly stronger on the volar than on the dorsal side. The ring effect is unmistakable when the hand is moved up and down in the water.

27. Pressures are not Equally well Perceived in all Parts of the Body. This may be tested with weights applied somewhat as in Ex. 24, as was done by Weber, but a simpler experiment may be made as follows: Find the pulse at the wrist; feel it with the finger tips, the back of the fingers, the side of the hand, the other wrist, the lip, and the tip of the tongue. Try the pulse in the temple with the finger tips, the side of the hand, and the fore-arm. Notice that when it is felt by another person the experimenter is unable to feel it subjectively.

Goltz.

28. Refinement of Active Pressure Sense. Something of the refinement of the pressure sense in perceiving the unevenness of surfaces may be found by laying a hair on a plate of glass or other hard, smooth surface and over it 10 or 15 sheets of writing-paper. The position of the hair can easily be felt by passing the finger tips back and forth over the paper.

29. The Hairs as Organs of Touch. The finest hairs respond with a distinct sensation of anticipatory touch, when they are moved, and probably this accounts for a part at least of the differences between the fore-arm and finger tips found in Ex. 22. Touch a few single hairs and observe the sensation.

Blaschko.

30. The Feeling of Traction or Negative Pressure has

been discriminated by some authors, but has rarely been made an object of experiment. It is to be observed when viscid substances are handled, when a portion of the skin is brought over the mouth of a closed vessel and the air exhausted, or when in any other way the skin is lifted from the underlying portions of a member. The sensation may be studied qualitatively by passing a thread through a small bit of court-plaster, knotting it on the gummed side and sticking the plaster to the skin. Traction on the thread now produces the sensation.

Hall and Motora, 93 ff.; Bloch.

General Sensations, Tickle, and Pain.

These topics, though clearly of very great psychological interest, have so far received comparatively little careful study, and few experiments have been made upon them. They are not exclusively dermal senses, but the skin offers the most convenient field for the study of the two to be considered here, namely, tickle and pain. In both the experimenter should notice the subjective cast of the sensations. Our eyes and ears give us information about colored and sounding things, but tickle and pain let us know that *we* are being tickled or hurt by something.

31. Tickle. Two sorts of tickle are easily distinguishable, a deep-seated tickle located in the rib region, which seems more strongly developed in children, and responds to rather strong stimulation, and a superficial tickle much more widely distributed, and responding to slight stimuli only. The latter sort is that regarded in this group of experiments.

a. Touch very lightly the different parts of the face, especially about the eyes, the margin of the lips and the opening of the ears with the tip of a light wisp of paper and notice the tickle sensations. Notice the apparent

disproportion between the stimulus and the resulting sensation, the wide and indefinite irradiation, and the long after-image.

b. Touch the same parts as lightly as possible with the tip of a penholder or the finger, and then with the same instrument while exerting at the same time a moderate pressure. Notice the difference in effect; notice also that the tendency to rub a tickled surface is a tendency to use a greater stimulus to remove the effects of the less. Notice also, when feeling a tendency to sneeze, that the sneeze can be wholly prevented by firm pressure or rubbing of the sides of the nose or the adjacent parts of the face.

c. Tickle is apparently a summation phenomenon. Touch the tip of the tongue lightly with the prong of a tuning-fork at rest and notice the after-image, which, however, has no tickle in it. Then strike the fork and touch it to the tip of the tongue. Compare the effects.

d. The ticklability of adjacent parts of the body is quite markedly different. Test with the tuning-fork, striking it and applying it gently to the tip, sides, and middle of the upper surface of the tongue and to the lower surface.

32. Pain. *a.* Slow conduction. Remove the shoe and strike a smart blow with a light rod on the sole of the foot. or on a corn; the pain will be perceived noticeably later than the first sensation of contact, separated from it perhaps by an almost empty interval. This delay is probably due to the same cause as the secondary after-image of touch in Ex. 11.

b. Temperature pains. A given increase of heat above the blood temperature is more effective in causing pain than an equal decrease. Compare the effects of plunging the hand into water at 10°C. and at 60°. Use a considerable quantity of water and do not allow the hand to remain too

long in the water, for its sensibility to pain as well as to temperature is decreased by fatigue.

Experiments on pain can likewise be made with electrical stimulation and pressure. These are especially suitable for determining the relative sensibility of different subjects. The first can easily be tried with the sliding induction coil, by applying the electrodes to the surface to be tested and then gradually pushing the secondary coil towards the primary till the stimulation becomes painful. For apparatus, see the chapter on apparatus below.

Weber, 569 ff.; Dessoir, Beaunis, Lombroso, Mantegazza, Preyer, 89.

BIBLIOGRAPHY.

In the following bibliography, and those appended to later chapters, the aim has not been to make an exhaustive list, but rather to give a number of the more important references by which the student may begin the study of original sources if he desires. For the same reason the list has not been kept strictly to works where the experiments of the chapter are discussed, but a few other important references have been given. If any one wishes to increase the list, he can easily do so from the reviews in the various philosophical and psychological journals, and from the classified bibliography on psychology and the physiology of the sense organs published yearly in the *Zeitschrift für Psychologie*, beginning with the literature of 1889. For the older literature the rich citations of Volkmann's Lehrbuch der Psychologie may be consulted. Much psychological literature appears at present in the physiological periodicals. The *Centralblatt für Physiologie* contains reviews and an annual bibliography of general physiology, with sections on the physiology of the senses and physiological psychology, and has done so since its beginning, in 1887. Hermann's Handbuch der Physiologie makes many references to literature, and each important section in Beaunis's Éléments de Physiologie humaine is followed by a bibliography. Hoffmann and Schwalbe's Jahresberichte über die Fortschritte der

Anatomie und Physiologie gives bibliographies and summaries of literature since 1872. The *Index Medicus*, now in its fifteenth volume, has listed all current medical literature since 1879 ; and in connection with this may be mentioned the mammoth Index Catalogue of the Library of the Surgeon-General's Office, United States Army, of which thirteen large volumes have so far been published (September, 1893), extending from *A* to *Sutugin*. The descriptive pamphlet of the Harvard Psychological Laboratory also contains, in a ten-page appendix, a classified list of psychological literature.

ARISTOTLE: Περὶ Ενυπνίων, c. 2, Bekker, 460. Also in German translation by Johannes Müller, as an appendix to his Ueber die phantastischen Gesichtserscheinungen. Coblenz, 1826.

AUBERT UND KAMMLER: *Moleschott's Untersuchungen*, V., 1859, 145.

BEAUNIS : Les Sensations internes, Paris, 1889.

BLASCHKO: Zur Lehre von den Druckempfindungen, Verhandl. d. Berliner physiol. Gesell., Sitz. 27 März, 1885. *Du Bois-Reymond's Archiv*, 1885, 349.

BLIX : Experimentelle Beiträge zur Lösung der Frage über die specifische Energie der Hautnerven, *Zeitschrift für Biologie*, XX., 1884, 141–156.

BLOCH: Recherches expérimentales sur les sensations de traction et de pression cutanées, *Archives de Physiologie*, Sér. 5, III., 1891, 322–333.

BRONSON : The Sensation of Itching, *Medical Record*, XXXVIII., 1890, No. 1041, Oct. 18, 425–429.

DESSOIR: Ueber den Hautsinn, *Du Bios-Reymond's Archiv*, 1892, 175–339. See review of this paper by Goldscheider, *Zeitschrift für Psychologie*, V., 1893, 117–122.

DONALDSON: On the Temperature-sense, *Mind*, X., 1885, 399–416.

DU BOIS-REYMOND, RENÉ: Ueber chemische Reizung des Temperatursinnes. Verhandlungen der Berliner physiol. Gesellsch., Sitz. 11 Nov. 1892. *Du Bois-Reymond's Archiv.*, 1893, 187–190.

FECHNER: Elemente der Psychophysik, I., 201–211 (temperature).

FUNKE: Der Tastsinn und die Gemeingefühle, *Hermann's Handbuch der Physiol.*, Vol. III., pt. 2, 289–414.

GOLDSCHEIDER: *A.* Ueber Wärme-, Kälte- und Druckpunkte, Verhandl. d. Berliner physiol. Gesell., Sitz. 13 März, 1885. *Du Bois-Reymond's Archiv*, 1885, 340–345.

B. Neue Thatsachen über die Hautsinnesnerven. *Ibid.* 1885, Supplement Band, 1–110, 5 plates.

C. Zur Dualität des Temperatursinns, *Pflüger's Archiv*, XXXIX., 1886, 96–120. (On Herzen's experiments.)

D. Ueber die specifische Wirkung des Menthols auf die Temperatur-Nerven, Verh. d. Berliner physiol. Gesell., 9 April, 1886. *Du Bois-Reymond's Archiv*, 1886, 555.

E. Histologische Untersuchungen über die Endigungsweise der Hautsinnesnerven beim Menschen. *Ibid.* 1886, Supplement-Band, 191–231.

F. Die Einwirkung der Kohlensäure auf die sensiblen Nerven der Haut, Verh. d. Berliner physiol. Gesell., 4 Nov. 1887. *Ibid.* 1887, 575–580.

G. Ueber die Topographie des Temperatursinns, Verh. d. Berliner physiol. Gesell., Sitz. 1 Juli, 1887. *Ibid.* 1887, 473–476.

H. Ueber die Summation von Hautreizen, Verhandlungen der physiol. Gesellsch. zu Berlin, Sitz. 31 Oct. 1890. *Ibid.* 1891, 164–169.

I. Die Lehre von den specifischen Energieen der Sinnesnerven, Berlin, 1881. A forty page dissertation, containing full references to literature.

GOLTZ: Ein neues Verfahren die Schärfe des Drucksinns der Haut zu prüfen, *Centralblatt für med. Wiss.*, 1863, No. 18, 273–276.

HALL AND DONALDSON: Motor Sensations of the Skin, *Mind*, X., 1885, 557–572.

HALL AND MOTORA: Dermal Sensitiveness to Gradual Pressure Changes, *American Journal of Psychology*, I., 1887, 72–98.

HERING: Der Temperatursinn, Hermann's Handbuch der Physiologie, Vol. III., pt. 2, 415–439.

HERZEN: Ueber die Spaltung der Temperatursinnes in zwei gesonderte Sinne, *Pflüger's Archiv*, XXXVIII., 1886, 93–103.

HOPPE: Das Aristotelische Räthsel der mit den gekreuzten Fingerspitzen gefühlten Kugel, *Wiener med. Presse*, 1888, Nos. 22, 23, 785, 827.

James: Principles of Psychology, New York, 1890.

Ladd: Elements of Physiological Psychology, New York, 1887.

Loeb: Untersuchungen über den Fühlraum der Hand, *Pflüger's Archiv*, XLI., 1887, 107–127.

Lombroso: Algometria elettrica nel uomo sano e alienato, Milano, 1867.

(Lombroso und Ottolenghi) Die Sinne der Verbrecher, *Zeitschrift für Psychologie*, II., 1891, 337 ff.

Lotze: *A.* Medicinische Psychologie, Leipzig, 1852.

B. Outlines of Psychology, translated by Herrick, Minneapolis; also by Ladd, Boston, 1885.

Mantegazza: La Physiologie de la Douleur, Paris, 1888.

Preyer: Ueber den Farben- und Temperatur-Sinn mit besonderer Rücksicht auf Farbenblindheit, *Pflüger's Archiv*, XXV., 1881, especially pp. 75–92.

Quincke: Ueber Mitempfindungen und verwandte Vorgänge, *Zeitsch. für klin. Medicin*, XVII., 1890.

Schwaner: Die Prüfung der Hautsensibilität vermittelst Stimmgabeln bei Gesunden und Kranken, Inaug. Diss., Marburg, 1890, 37. Review with table of sensibility, *Zeitschrift für Psychologie*, II., 1891, 398.

Sergi: Su alcuni caratteri del senso tattile, *Rivista di Filosofia Scientifica*, 1891. Same paper in German, *Zeitschrift für Psychologie*, III., 1892, 175–184.

Stumpf: Zum Begriff der Lokalzeichen, *Zeitschrift für Psychologie*, IV., 1892, 70–73.

Szabadfoeldi: *Moleschott's Untersuchungen*, IX., 1865, 631.

Vierordt: Physiologie des Menschen, Tübingen, 1877, 340 ff.

Weber: Der Tastsinn und das Gemeingefühl, Wagner's Handwörterbuch der Physiologie, III., 2, 481–588.

Von Wittich: Bemerkungen zu Preyers Abhandlung über die Grenzen des Empfindungsvermögens und Willens, *Pflüger's Archiv*, II., 1869, 329–350.

Wundt: Grundzüge der physiologischen Psychologie, 3te Aufl., Leipzig, 1887, I., 391 ff., II., 5 ff.; 4te Aufl., Leipzig, 1893, I., 410 ff.

For further bibliographical references see especially the citations of the following authors: On Touch, Dessoir and Goldscheider. On Temperature, Dessoir, Donaldson, Goldscheider. On Pressure, see bibliographies following the chapter on Weber's Law and the account of pressure sense apparatus below. On Pain in general, see Bain, *Mind*, Ser. 2, I., 1892, 161; Marshall, *Ibid.* Ser. 1, XIV., 1889, 511; XVI., 1891, 327, 470; Ser. 2, I., 1892, 358, 453; *Philosophical Review*, I., 1892, 625; Nichols, *Ibid.* I., 1892, 403, 518.

CHAPTER II.

Kinæsthetic and Static Senses.

THIS group of senses furnishes us data for the perception of the positions and motions of our members and of the body as a whole, and plays a leading part in the perception of space. It includes some senses whose existence or efficiency is disputed (Innervation Sense[1] and Muscle Sense), and others whose independence has only of late been generally recognized (Joint Sense and Tendon Sense). All are closely united with one another and with pressure and contact, and some are hardly ever dissociated except by disease. This chapter is necessarily limited to the experimental side of the subject and to the simpler experiments to be found there. Many of the most important psycho-

[1] The term "innervation sense" must not be taken too strictly as meaning a wholly independent sense of motor discharge, as it has often been taken. Says Wundt, in his last edition (4te Aufl. I., 425): "Manifold observations make it probable that the central components of the sensations accompanying active movements have their origin in the memory-images of movements previously executed, which partly initiate, partly accompany, each voluntary movement. Since memory-images possess qualitatively the same sensory content as the original perceptions, such central sensations of effort and movement (*Kraft- und Bewegungsempfindungen*) will under normal conditions blend completely with the more intense peripheral sensations of the same kind; they will, however, produce an independent effect, if from any cause the peripheral sensations fall away. It would be proper, therefore, to give up the term "innervation sensations" for the sensations in question; because it is liable to convey the false impression that these are sensations which in and for themselves, without any relation to the peripheral components of the sensations of effort and movement, accompany the motor innervation. This assumption, which as a rule has formerly been connected with the notion of "innervation sensations," is, however, very improbable." Cf. also p. 431, and in the third edition I., p. 405 ff.

logical problems involve the motor sensations of the eye, some of which are considered in Chap. VII.

MUSCLE SENSE, *Kraftsinn.*

Whether there are any specific muscular sensations distinct from those that come from other parts of the member in motion cannot now be asserted with positiveness; but even if there be such, the part that they play in our ordinary motor perceptions is probably a minor one. The term "muscle sense," however, has been used to designate the whole group of motor sensations, and is here retained for that purpose.

33. Lifted Weights. *a.* Weights lifted slowly seem heavier than the same weights lifted rapidly. Lift the same weight twice, lifting it first at the most natural and convenient rate, and the second time very slowly, beginning with much less than the necessary effort and gradually increasing it till the weight rises.

b. Lift a moderate weight with one hand and at the same time clench the other sharply. The weight will seem lighter than when no simultaneous effort is made.

c. Repeat Ex. 23, using active lifting instead of pressure in comparing the weights.

Charpentier; on *a*, Goldscheider, *A*, 186.

34. Discriminative Sensibility for Lifted Weights.

a. Find by the method of experiment used in Ex. 24 what is the just observable difference above and below a standard weight of 100 grams, when the weights are lifted instead of merely being allowed to press upon the skin. In this experiment lift the weights successively with the same hand. The weights must be placed near together within convenient reach, and care must be taken that both are lifted at the same rate and to the same height. Let the subject lift one

weight and then the other, and render his decision after once lifting each. In half of the trials let the standard weight be placed at the left side of the weight to be compared and be lifted first; in the other half let the weight to be compared stand at the left and lead in the lifting.

b. Repeat the experiment, letting the subject lift the standard with one hand, and the comparison weight with the other, keeping the same hand for each during each set of trials (that is, during a determination of the just observable difference above and below), but combining a number of sets with the standard in the right hand with an equal number in which it is in the left. Find also from the figures the ratios when the standard is in the right hand and when it is in the left hand, for use in Ex. 35. Compare the ratios found in these experiments with that found in Ex. 24.

In these experiments the sense of pressure might be expected to co-operate; but when it is excluded, or put at a relative disadvantage, the sensibility for differences of lifted weights is not diminished. Weber's method of excluding the pressure sense was to wrap the weights in pieces of cloth, and lift them by the four corners together. The pressure on these corners can be changed at will, irrespective of the heaviness of the weight lifted.

For fuller literature on lifted weights, see the chapter on Weber's Law below.

Weber, 546–547; Müller und Schumann; James, II., 189 ff., 486 ff.; Beaunis; Wundt; Fullerton and Cattell.

35. Adjustment of the Motor Discharge. After having performed the second part of Ex. 34, compare the standard weight with a very much heavier weight, e.g., 2 kg., with all the circumstances of actual careful judgment. Practise this judgment thirty times, leaving a longer time between

the individual comparisons than between liftings of the weights compared. Then at once return to the smaller weights, giving the standard to the same hand as before, and to the hand that has just been lifting the 2 kg. the weight to be compared. Not only will the weight just recognizably heavier before seem considerably lighter than the standard, but also still heavier weights will seem so. This time the tests must be few, not more than three or four. If more tests are desired, practise the comparison of the standard and 2 kg. weight again ten times before taking them. By the practice the nervous centres discharging into the muscles that raise the 2 kg. weight become accustomed to a larger discharge than that required for the small weights and do not at once re-adapt themselves, but supply too great a discharge. The weight now rises with greater rapidity than the standard, and is consequently pronounced lighter (Müller and Schumann), or the balance between the extensors and flexors that was suited to raising the heavier weight is not suited to the lighter weight, and the second is pronounced lighter because of the strain in the extensors necessary to restore the balance (Delabarre). This experiment seems conclusive against a well-developed and independent innervation sense; for if there were any sensation of nervous discharge, we ought to know when we go from a very heavy to a light weight that the discharge is disproportionate; but we do not.

Müller und Schumann; but cf. also Fullerton and Cattell, 131, and Delabarre.

INNERVATION SENSE.

36. Simultaneous Movements. The evidence most frequently offered in support of a special innervation sense is clinical and therefore beyond the scope of this course. Experiments of the type of the following have been brought forward, but their interpretation has been disputed.

a. Stand erect before the blackboard, with the eyes closed and coat off, if it interferes with free motion of the arms. Draw with each hand, using both at once, a conventional leaf pattern like those in the annexed cut, drawing always from *a* to *b*. In drawing, try to make the lobes of the leaf of equal size, like those in Fig. 1; draw each with a single simultaneous "free-hand" motion of the arms, that is, draw each with a single volitional impulse directed equally to the two sides; the last point is important. First draw a pair of leaves, beginning them with the hands before the shoulders at the same height; the result will be approximately like Fig. 1. Next draw a pair with one hand about a foot higher than before, the other about a foot lower; the result will be like Fig. 2.

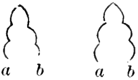


Fig. 1.

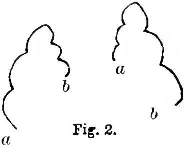


Fig. 2.

b. Bring the hands again to the position used in drawing Fig. 1, and draw a pair of leaves having their apices right and left. The leaves will be symmetrical. Next begin with one hand about a foot farther away from the median plane than before and the other at it, but both at the same level. Draw as before; asymmetrical leaves will be the result. Repeat the drawing a number of times, sometimes raising or extending one arm, sometimes the other. In general it will be found that, notwithstanding the intention to make equal movements of the hands, the motions of further extension in the extended arm and of further flexion in the flexed arm are too short, and those in the contrary direction in each case too long. The argument founded on this experiment runs as follows: We think that our hands execute equal movements, when they do not, because we are conscious of willing equal movements, and unconscious, or only

inexactly conscious, of those actually made. If we perceived motion of our members by the skin, joint, and muscle sensations that accompany their motion (as the opponents of the innervation sense believe) we ought to know the extent to which our hands are moved each time, and not to fall into the illusion that we find in these experiments. Cf. Ex. 44 *d*.

Loeb, *B*, 15 ff.

37. Illusory Movement in an Immovable Member. Lay the hand palm downward on the edge of the table or on a thick book so that the last three fingers shall be supported and held extended while the thumb and first finger remain free. Bend the first finger considerably at both the inner joints, and hold it in position with the other hand. The finger-tip is still movable, as will be found on touching it; but it is anatomically impossible to move it voluntarily. When, however, the effort is made to move it (the eyes being closed), there is a sensation of motion, though no actual motion is possible. From this, an inner sense of motion (innervation sense) has been inferred. When operating upon another subject, the operator may hold the finger in position, and require the subject to execute with the corresponding finger of his free hand a motion equal to that which he thinks he makes with the one that is held. Observe, however, that the tendons in the wrist move, and that there are slight movements elsewhere in the hand.

Sternberg; James, II., 105, 515, footnote; Goldscheider, *A*, 317.

38. Ferrier's Experiment. That the feeling of effort is largely, if not entirely, of peripheral rather than central origin, appears from such experiments as the following. Hold the finger as if to pull the trigger of a pistol. Think vigorously of bending the finger, but do not bend it; an unmis-

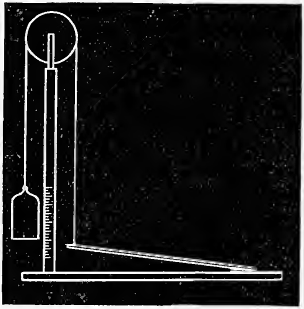
takable feeling of effort results. Repeat the experiment, and notice that the breath is involuntarily held, and that there are tensions in other muscles than those that would move the finger. Repeat the experiment again, taking care to keep the breathing regular and the other muscles passive. Little or no feeling of effort will now accompany the imaginary bending of the finger.

Ferrier, 382 ff. (English Ed.).

On Innervation Sense in general, besides the authors already mentioned, see : Wundt, 3te Aufl. I., 397 ff., 4te Aufl. I., 423 ff.; James, II., 486 ff.; Goldscheider, *A*, 206 ff.

SENSATIONS OF MOTION, JOINT SENSATIONS.

39. Passive Motion at the Elbow. Let the subject rest his fore-arm flat upon the arm-board of the instrument (bringing his elbow over the hinge), and close his eyes. Let the operator then raise or lower the free end of the arm-board slowly by pressing down or lifting the counter weight, and require the subject to announce when he first perceives the motion of his fore-arm. Record the angular movement required to produce a just observable sensation. Notice that the movement seems to be located chiefly in the hand. It is extremely important not to mistake the sensation of increased pressure or of jar for that of motion. The rate of movement will be found important, and should be



kept as constant as possible. The results found in this way are rough; for more exact methods see Goldscheider, *A.*

40. Active Movement of the Last Joint of the Finger. The joint sensations of the fingers are less fine than those of the elbow, but are more convenient for demonstration of active flexion. Fasten a piece of straw, with court-plaster or otherwise, to the finger-nail of the middle finger, and cut it off at such a length that the distance from the joint of the finger to the end of the straw shall be 115 mm. With that radius 2 mm. corresponds to about 1° of angular measure. Rest the hand on a thick book, letting the last joint of the finger extend beyond the edge. Set up a millimeter scale at right angles with the straw. Close the eyes and make the least possible flexion of the finger at the last joint, having an assistant note its extent on the scale. Close attention may perhaps be able in both the active and passive movements to locate the sensation in the joint, but more rigorous experiments are required to show its character clearly, and to prove its location.

Goldscheider, *A.*

41. Location of Movements. *a.* Motions on the skin can be interpreted either as the movement of an object over the surface of the skin, or of the skin over the surface of the object. This opens the way for illusions. Have an assistant draw a pencil-point gently across the wrist or the finger-tips of the observer, who sits with closed eyes. A tendency to interpret the sensation as motion of the wrist or finger will be observed. The hand and arm must be held free, so that the illusion may not be corrected by the presence of other touch sensations.

b. With the eyes closed, move the wrist or finger over a stationary pencil-point. In this case the point also seems to be in motion in a direction contrary to that of the hand.

c. When the movement may be interpreted as belonging to either of two members, it may be credited to the more mobile of the two, or may be shared by both. Rest the finger lightly on the forehead; then, taking pains to keep its position fixed, move the head from side to side. There is a strong tendency to credit the motion to the finger and arm. Hold the last three fingers close together, and move the first away from them and toward them again. All will seem to move, but the last three in an opposite direction to the first.

d. Ex. 4 above is an experiment on the location of movements as well as of touches. If the cane is swung so as to describe the surface of a cone we are conscious of the path described by its point, as well as that of the hand holding it. Cf. Ex. 39 where the motion of the whole fore-arm and hand is credited chiefly to the latter.

Vierordt; on *c*, Goldscheider, *A*, 181 ff.

42. Interrupted Extent may seem smaller to a moving member than uninterrupted. In a piece of cardboard make three pin-holes in a line separated by spaces of an inch and a half. Fill one of the spaces with pin-holes a quarter of an inch apart. Turn the card over, close the eyes, and move the finger-tip across the little eminences made by the pin-holes. The illusion seems more marked when the finger moves over the interrupted half of the line first. Examine the card visually, and notice that the visual illusion is in the directly opposite sense. As in the similar touch experiment above (Ex. 8) the results are apparently not equally clear for all observers.

James, II., 250.

Sensations of Resistance.

43. Illusory Resistance. *a.* Hold a heavy weight by a string so that it hangs, with the arm extended, a few inches

above the floor, or better, have the string placed in the hand by an assistant so that the length of the string may not be known beforehand. Lower the weight rather rapidly till it rests on the floor or other support. As it strikes, a sensation of arrest will be perceived, somewhat as though the hand were suddenly supported by a light rod. The illusion is even more marked when the string, instead of being held in the hand, is fastened to a small rod, and that is held. The disturbing noise of the weight may be obviated by having it come to rest on a cushion or in a box of sand. The illusion is due to the unexpected strain put upon the muscles that lower the arm by the tension of those that have been holding the weight. This feeling of arrest is probably a joint sensation. To distinguish this sensation from the motion sensations of the joints, Goldscheider has called it a "joint-pressure sensation."

b. When the movement of the rod is continued downward beyond the point at which the sensation of arrest is felt, a certain difficulty of movement may still be observed, as though the rod were moving through a resisting medium. This sensation Goldscheider distinguishes from the sensation observed in *a*, believing it to be the true sensation of difficult motion (of weight and heaviness also) and crediting it to the tendons.

c. Notice something similar to *b* in pouring a quantity of mercury rapidly from one vessel to another.

It is evident that such illusions as these speak against the existence of an innervation sense in the common acceptation of the term.

Goldscheider, *A*, 164 ff., 172 ff., *D;* on *b*, *A*, 188; Mach, *A*, 70 ff.

Bilateral Asymmetries of Position and Motion.

44. Apparently Symmetrical Motions of the arms. In all the tests of this group, the subject should be kept in ignor-

ance of the nature and amount of his errors till the tests are finished.

a. Hold an ordinary cork between the thumb and first two fingers of each hand. Close the eyes and bring the two corks together at arm's length in the median plane before the face, having an assistant note the approximate amount and direction of the error. The corks should be brought together rather gently, so as not to betray the character of the error to the operator, but the motions of the arms by which they are brought up nearly to contact should be free and sweeping. The error will probably be found rather constant in direction until the operator learns to correct it. Try bringing the corks together above the head, and also in asymmetrical positions.

b. Let the subject seat himself at a table with the millimeter scale before him. Set a pin in the middle of the scale, and bring the pin into the median plane of the subject and make the scale parallel to his frontal plane. Let the subject place his forefingers on either side of the pin, and, with closed eyes, try to measure off equal distances by moving both simultaneously outward along the scale. Note the result in millimeters; for this it may be convenient to mark the middle point of the finger-nails with an ink-line. A constant excess in the motion of one hand or the other will often be found. It is important that the subject should not open his eyes till his fingers are removed from the scale; for he will find it difficult not to correct his error if he knows its nature. The finger-tips should rest lightly on the scale, and the motions should be made from the shoulder by a single impulse; if they are too slow, and the subject attends to his sensations of position, the errors will be small and uncertain. The left hand, it is said, generally makes the greater excursion in right-handed persons not mechanics.

c. Repeat the tests, having the motions of the hands made

successively instead of simultaneously. The constant difference between the hands will probably not appear.

d. Let the subject start with his right and left hand each 20 cm. toward its own side of the median plane, and try to measure off equal distances on either side of those points, moving both hands at once in the same direction. Distances inward will be made too large, distances outward too small. In all these experiments with closed eyes we seem inclined to judge distance rather from the intention of equal motion and the continuance of motor sensations for equal times, than from the actual peripheral sensations.

The judgments of symmetry of position and motion rest upon very complex combinations of the dermal and kinæsthetic sensations, already made the subject of experiment above. As a result of this complexity the experiments of this group will be found to give rather variable results, from one subject to another, and in the same subject at different times.

Hall and Hartwell; Loeb; Delabarre; Bloch.

RECOGNITION OF THE POSITION OF THE BODY AS A WHOLE.

45. Recognition of Direction. In this experiment it is especially desirable that the subject should know as little as possible of the purpose of the experiment. Cause him to stand erect with his back against a wall. Choose a point on the opposite wall about the height of his shoulders. Let him look at it, and then require him, having closed his eyes, to point to it as exactly as possible with a light rod held symmetrically in both hands. Cause him also to hold the rod vertically and horizontally in the median plane; also horizontally parallel to the frontal plane. All these he will probably be able to do with much accuracy; or if, as sometimes happens, he shows a "personal equation," his error will be constant.

a. Cause the subject to repeat the experiment, this time turning his head as far as possible to the left after closing his eyes, taking pains to keep his shoulders square. Repeat, causing the subject to turn to the right. In both cases an error will be observed, the subject pointing too far in a direction opposite to that of the turning of the head. The subject will be able to hold the rod vertically, or horizontally, without error. Cause the subject to hold the rod in what he thinks is a horizontal position, in the median plane when his head is thrown well back; when bowed well forward. Illusions like those observed above, affecting directions in the plane of movement of the head, will result. Cause the subject to hold the rod in what he thinks is a horizontal position, parallel to the frontal plane, when his head is bowed to the right; when bowed to the left. Illusions similar to those in the previous experiments will appear. In all these cases judgment of one cardinal direction in space alone is affected; the other two show little or no errors.

b. Repeat the first part of experiment *a;* but instead of having the subject point to the designated object, have him walk toward it, keeping his shoulders square, his eyes shut, and his head turned to one side. He will walk more and more too far toward the side away from which his head is turned.

c. The illusion is due, at least in the case of turning the head about a vertical axis, to the position of the eyes; the eyes turn farther than the head in the direction in which it is turned, as may easily be observed upon any other person. From the eyes we judge the position of the head, and thus overjudging it, point too far in a contrary direction in trying to point to the required object (Delage). The illusions can be produced by motion of the eyes alone. Holding the head erect, and taking pains not to move it when moving the eyes, turn the closed eyes as far as possible to the right

or left, and then try to point to some determined object. An error like that in *a* will be observed. Turning of the eyes upward or downward has a doubtful result. Instead of closing the eyes, they may be kept open if an opaque screen is held close before the face. Repeat *a*, voluntarily turning the eyes as far as possible in the direction opposite to that of the turning of the head. The original error will probably disappear, or be found to have changed its sign.

For this illusion another eye explanation is suggested by Breuer, namely, that in such extreme turnings of the eyes, their actual position does not correspond with the intended position, but comes short of it. We infer the direction, however, from the intended position, and thus fall into the error in pointing. For the illusion in other positions of the head and even for this, his own preferred explanation is again different, and is partly based on the following experiment.

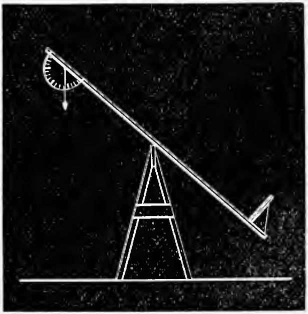
d. Close the eyes, and touch the tip of the nose or the forehead with a pin or a pencil while the head is in the usual position, and after a little try to touch the same spot again. The error, if any, will be very small. Repeat the touch in the normal position, and then turn the head to the right or left or incline it toward the shoulder or forward or backward. After holding it in the chosen position for half a minute, attempt to touch the spot again. Gross errors will result till corrected by practice. The error is one of underestimation, and should by itself alone produce a result directly the reverse of that found by Delage. Breuer, however, introduces another factor. His explanation for the inclined positions of the head is somewhat as follows: by means of the otolith-apparatus of the ear, we get a true perception of the amount of inclination of the head, at the same time that we get the erroneous perception just mentioned. The only way in which we can harmonize the

conflicting perceptions is by altering our judgment of the vertical, and with that, of course, of the horizontal. For the movements of rotation about a vertical axis the semi-circular canals (See Exs. 47-49) would furnish the knowledge of the true amount of turning, and from a similar combination of the true and false the illusions in that case would result.

This group of experiments, except perhaps the last, when tried under the ordinary conditions of the practice laboratory, seems liable to considerable individual variation; but sufficient care, especially as to the position of the eyes in turning to the right and left, should lead to a tolerable degree of success.

Aubert (Delage), 17 ff.; Loeb, *B*, 20 f., 31 f.; Breuer, 270 ff.

46. Vertical and Horizontal Positions of the Body. Secure the subject properly upon the tilt-board, and have him close his eyes. Start with the board vertical (head up). Require the subject to describe his position. He will probably announce that he is then leaning forward slightly. As a matter of fact he is, if his heels are against the board. Turn him slowly backward, and require him to say when he seems to himself vertical (head up), when he seems tilted backward at an angle of 45° from the vertical, when at an angle of 60°, when at 90°, when at 180°. Two classes of illusions will be found: angles of less than 40° will probably seem too small; those from 40° to 60° will be rightly



judged; those beyond 60° will seem too large. The subject will say that he is vertical, head downward, when he is yet 30–60° from it. The subject may be allowed a pillow if he desires it.

The illusions depend in large measure on the distribution of pressure on the soles and other surfaces of the body and the direction of pressure of the movable viscera and the blood.

Aubert (Delage), 40 ff.; Breuer, 270 f.

SENSATIONS OF ROTATION.

47. Perception of Uniform Rotations. Let the subject be seated upon the rotation table with closed eyes, blindfolded if necessary. Turn the table slowly and evenly in one direction or the other. The subject will immediately recognize the direction and approximately the amount of rotation when the rate is as slow as 2° per second, or even slower. After continued rotation at a regular rate the sensation becomes much less exact or entirely fails. This fact has been generalized by Mach in the law that only change of rate, not continuous rotation, is perceived. After some pauses and short movements in one direction and the other, the subject may become quite lost, and give a totally wrong judgment of the direction of motion, if it is slow.

48. Illusion of Backward Rotation. Let the subject be seated as before. Rotate him a little more rapidly for half a turn, and then stop him suddenly. A distinct sensation of rotation in the opposite direction will result. Repeat, and when the illusory rotation begins, open the eyes. It immediately ceases. Close the eyes again, and, if strong, it again returns.

49. Location of the Organs for the Perception of Rotation. *a.* Repeat the first part of Ex. 48, letting the subject

give the word for stopping. At the same instant let him incline his head suddenly backward or forward, or lay it upon one shoulder or the other. The axis of rotation of the body will appear to change in a direction opposite to that of the inclination of the head; i.e., if the head is inclined to the right, the axis seems to incline to the left. The feeling is as if the body were rotating in the surface of a cone in a direction contrary to that of the first rotation. The head dictates the apparent axis of rotation. The same illusion occurs if the head is inclined during the actual rotation and straightened at the word for stopping. Turning the head to the right or left introduces no such illusion, because it does not change the axis of rotation of the head. The illusion comes out with very disagreeable strength when the rotation is rapid, and the subject changes the position of his head during the rotation.

b. Let the subject lie upon his side, and rotate him rather rapidly till the sensation of rotation becomes faint or disappears. Then let him turn suddenly upon his back or upon his other side. Turning upon his back starts rotation about a new axis, and it is felt in its true sense, while the rotation about the previous axis is felt as an illusion in its reverse sense. The resulting perception combines both. Turning completely over reverses the direction of motion completely, and the combined sensation and illusion produce a correspondingly powerful effect.

The change of the apparent axis of rotation with the change of position of the head points to the location in the head of the organ for such sensations. For the experiments by which the semicircular canals are indicated as this organ, and the arguments pro and con, see the literature cited by Aubert, Ayres, and others.

On the last three experiments, see: Aubert (Delage), 49 ff.; Brown; Mach; Wundt, 3te Aufl., I., 211 f.; II., 24,139.

50. Another Illusion of Rotation (Purkinje's dizziness) is due to involuntary motions of the eyes. Let the subject whirl rapidly on his heels with his eyes open till he begins to be dizzy. At first objects about him seem at rest, then to be turning in the opposite direction. Let him now stop and look at an even surfaced wall while the experimenter carefully observes his eyes, picking out some clearly marked fleck or spot as a point of observation. To the subject the surrounding objects will seem to continue to move in the same direction as before; i.e., in a direction contrary to his previous rotation; the experimenter will see the subject's eyes executing slow motions in one direction (in the direction of the original motion of the subject) alternating with rapid motions in the other. The subject himself may be able to perceive a corresponding irregularity of motion in the spots upon the wall at which he looks. He can easily observe the motions of his own eyes if he looks fixedly for twenty or thirty seconds at a flame or a strip of white paper in a bright light before beginning his rotation; the after-image (see Chapter V.) thus produced remains fixed on the retina, and its apparent movements betray the motions of the eye. If the eyes are closed after the rotation, the image will seem to move in one direction, and rather slowly. The illusion rests upon the subject's unconsciousness of the slow motions of his eyes. It is probable that these eye motions and the sensations of attempted restoration of equilibrium in other parts of the body are reflexly caused by the disturbance in the semicircular canals.

It should be noticed that this illusion is the exact reverse of that found with closed eyes in Ex. 48. There the subject feels a rotation of his own body contrary to that it previously received. If he was turned at first in the direction of the hands of a watch, on being stopped he would seem to be turning in a direction contrary to the hands. If these

motions were transferred to objects about him, they would, during the rotation, seem to move contrary to the hands, and after stopping, in the direction of the hands. In the Purkinje experiment the motion of objects is not thus reversed.

Those who try these rotational experiments should do so with caution, for the unpleasant effects of them sometimes last several hours.

Aubert (Delage), 52, 100 ff.; Mach. Aubert reprints Purkinje's paper on dizziness as an appendix to the translation of Delage.

Sensations of Progressive Motion.

51. Progressive motions, so far as they do not involve rotation, probably give us combinations of sensations from several different sources. The principle holds for progressive motions as for rotations, that we perceive changes of rate of motion, and not uniform motion; as long as the motion remains uniform we can by an effort of imagination conceive ourselves to be moving in either direction or to be standing still, except for what jarring there may be. The apparatus for the study of these phenomena will be found in railroad trains and elevators. See also Mach for special laboratory apparatus.

Aubert (Delage), 75 ff.; Mach; Brown; Breuer, 283.

BIBLIOGRAPHY.

Aubert: Physiologische Studien über die Orientierung, Tübingen, 1888, 122. This is a translation of the paper of Delage below, with full notes and appendix containing Purkinje's Bulletin von 1825, Ueber den Schwindel. See criticism by Breuer, 270 ff.

AYRES: *A.* A Contribution to the Morphology of the Vertebrate Ear, with a Reconsideration of its Functions, *Journal of Morphology*, VI., Nos. 1 and 2, May, 1892. Ayres gives a bibliography of nearly three hundred titles, many upon the psycho-physiology of the semicircular canals, but not a complete list.

B. The Ear of Man: Its Past, Present, and Future. Wood's Holl Biological Lectures, 1890. An Abstract of *A*.

BASTIAN: "The Muscular Sense;" Its Nature and Cortical Localisation, *Brain*, X., 1887–88, 1–89. Discussion on the paper by Ferrier, Sully, and others, 89–137.

BEAUNIS: Les Sensations internes, Paris, 1889.

BLOCH: Expériences sur les sensations musculaires, *Revue Scientifique*, XLV., No. 10, 1890, 294–301.

BREUER: Ueber die Function der Otolithenapparate, *Pflüger's Archiv*, XLVIII., 1890–91, 195–304.

BROWN: *A.* On the Sense of Rotation and the Anatomy and Physiology of the Semicircular Canals of the Internal Ear, *Journal of Anatomy and Physiology*, VIII., 1874, 327. Reprinted by Mach, *A*, 100.

B. On Sensations of Motion, *Nature*, XL., 1889, 449.

CHARPENTIER: Analyse expérimentale de quelques éléments de la sensation de poids, *Archives de Physiologie*, Sér. 5, III., 1891, 122–135.

DELABARRE: Ueber Bewegungsempfindungen, Inaug. Diss., Freiburg, 1891, 111. The author has also published a portion of the same matter in *Mind*, Ser. 2, 1892, 379–396.

DELAGE: Études expérimentales sur les illusions statiques et dynamiques de direction pour servir à déterminer les fonctions des canaux demicirculaires de l'oreille interne, *Archives de Zool. Expér.*, No. 4, 1886, 535–624 (with index). Translated by Aubert above. See also abstract of this paper in *Comptes rendus*, CIII., 1886, 749.

EWALD: Physiologische Untersuchungen über das Endorgan des Nervus octavus, Wiesbaden, 1892. Gives a very extended bibliography.

FERRIER: Functions of the Brain, London, 1886.

FULLERTON AND CATTELL: On the Perception of Small Differences, *Publications of the University of Pennsylvania, Philosophical Series*, No. 2, Philadelphia, 1892.

FUNKE: Der Tastsinn und die Gemeingefühle, Hermann's Handbuch der Physiologie, III., pt. 2, 289–414.

GOLDSCHEIDER: *A.* Untersuchungen über den Muskelsinn, *Du Bois-Reymond's Archiv*, 1889, 369 ff. and 540, also Supplement-Band, 1889, 141 ff.

B. Ueber den Muskelsinn und die Theorie der Ataxie, *Zeitschrift für klin. Med.*, XV., 1888–89.

C. Ueber die Grenzen der Wahrnehmung passiver Bewegungen, *Centralblatt für Physiologie*, I., 1887, 223–225.

D. Ueber paradoxe Widerstandsempfindung, *Ibid*, III., 1889, 90–91.

HALL AND HARTWELL: Bilateral Asymmetry of Function, *Mind*, IX., 1884, 93–109.

JAMES: Principles of Psychology, New York, 1890.

KREIDL: Beiträge zur Physiologie des Ohrlabyrinthes auf Grund von Versuchen an Taubstummen, *Pflüger's Archiv*, LI., 1891–92, 119–150.

LOEB: *A.* Untersuchungen über den Fühlraum der Hand; Erste Mittheilung, Gleiche Fühlstrecken, *Pflüger's Archiv*, XLI., 1887, 107–127.

B. Untersuchungen über die Orientirung im Fühlraum der Hand und im Blickraum, *Ibid.* XLVI., 1890, 1–46.

MACH: *A.* Grundlinien der Lehre von den Bewegungsempfindungen, Leipzig, 1875, 128. Gives bibliography of thirty-one titles.

B. Analyse der Empfindungen, Jena, 1886, 69 ff.

MÜLLER UND SCHUMANN: Ueber die psychologischen Grundlagen der Vergleichung gehobener Gewichte, *Pflüger's Archiv*, XLV., 1889, 37–112.

MÜNSTERBERG: Die Willenshandlung, Freiburg, 1888.

SCHAEFER: Die Erklärung der Bewegungsempfindungen durch den Muskelsinn, Inaug. Diss., Jena, 1889; also an article of similar title, *Pflüger's Archiv*, LXI., 1887, 566–640.

STERNBERG: Zur Lehre von den Vorstellungen über die Lage unserer Glieder, *Pflüger's Archiv*, XXXVII., 1885, 1. Gives bibliography of fifty-two titles.

VIERORDT: Die Bewegungsempfindung, *Zeitschrift für Biologie*, XII., 1876, 226–240. See also Vierordt's Physiologie, 5te Aufl., 329 ff.

WALLER: The Sense of Effort, *Brain*, XIV., 1891, 179–249, 433–436, especially 229 ff. This study is accompanied by a bibliography of fifty titles. Nearly the same portion of the paper indicated here as of special importance will be found under the following title: Experiments on Weight-discrimination, Proceedings of the Physiological Society, Session of Jan. 30, 1892, *Journal of Physiology*, XIII., May, 1892.

WEBER: Work cited in bibliography of Chap. I.

WLASSAK: Die statischen Functionen des Ohrlabyrinthes und ihre Beziehungen zu den Raumempfindungen, *Vierteljahr. für wiss. Philosophie*, XVI., 1892, 385–403, XVII., 1893, 15–29.

WUNDT: Work cited in bibliography of Chap. I., 3te Aufl., I., 397 ff., II., 21 ff.; 4te Aufl., I., 419 ff.

CHAPTER III.

Sensations of Taste and Smell.

These sensations are of secondary importance in psychology, and have received a correspondingly small share of investigation. In subjective quality they seem to stand midway between the general senses mentioned at the end of Chapter I. and the higher senses of Hearing and Vision.

Sensations of Taste.

52. Tastes and Smells. Much of what is commonly called taste is really a combination of taste with smell and with touch in its various forms. With the nostrils held, try to distinguish by taste alone between small quantities of water and a weak solution of essence of clove in water. A discrimination that is easily possible with the nostrils open is difficult or impossible with the nostrils closed. The solution should not be swallowed, for then the olfactory region may be reached from the back of the nose.

53. Distribution of the Organs of Taste. *a.* Using the weaker taste solutions, and operating upon yourself with a mirror or on another person, find out as nearly as you can in what part of the tongue the strongest sensations are produced by each. Test the tip, the sides, the back, and the middle, putting the solutions on with a camel's-hair brush, and rinsing the mouth as often as necessary. Try also the hard and soft palates.

b. Dry the tongue with a handkerchief, and test the individual fungiform papillæ with the stronger solutions,

applying them with fine camel's-hair pencils. It will be found possible to get taste sensations from the single papillæ, though perhaps not all four from each. Rinse the mouth as needed. Test the surface of the tongue between the papillæ and observe that no taste sensations follow.

a. Rittmeyer; *b.* Oehrwall.

54. Minimal Tastes. *a.* Find what is the greatest dilution of the weaker solutions in which the characteristic tastes can still be recognized. The same quantity, e.g., half a teaspoonful, should be taken into the mouth at each trial, and may be swallowed with advantage. Rinse the mouth thoroughly as required. The following are the average proportions found by Bailey and Nichols for male observers: Quinine, 1:390 000; Sugar, 1:199; Salt, 1:2240; for Sulphuric Acid, which they used instead of Tartaric, the proportion was 1:2080.

b. The intensity of the sensation and the greatest dilution still tastable depend on the number of taste organs stimulated. Take a portion of one of the solutions of just tastable strength, found in *a*, add an equal quantity of water, and take a large mouthful of the mixture. The characteristic taste will still be perceived, perhaps more strongly than before.

a. Bailey and Nichols, *A*; Lombroso und Ottolenghi; Camerer, *A*.
b. Camerer, *B*.

55. Discriminative Sensibility for Taste. For a rough determination, test with solutions of sugar, taking first a small quantity of the standard 20% solution, then an equal quantity (the equality is important) of one of the weaker solutions, or first one of the weaker and then the standard, until a solution is found that is just recognizably different from the standard. Make this determination several times. The excess of sugar in the standard solution over the

amount in the solution just observably weaker, set in a ratio to the total percentage of sugar in the standard, measures the sensibility. Some experimenters may be able to distinguish the 18% from the 20% solution; their sensibility would then be expressed by the ratio 2 : 20.

Keppler.

56. Electrical Stimulation. *a.* Using a constant current, from a single Grenet cell, for example, and two small zinc electrodes, one applied to the inner surface of the under lip and the other to the tongue, notice the sour taste at the positive pole and the alkaline at the negative.

Von Vintschgau, 181 ff.; Oehrwall; Hermann.

Sensations of Smell.

57. Minimal Odors. The keenness of smell may be tested with dilute solutions of odorous substances or with the olfactometer.

a. Test with solutions. Pour small quantities of the solutions of oil of cloves into little wide-mouthed bottles, filling each to about the same height. Mark all in an inconspicuous manner. Set the bottles a foot apart on a table in a place where there is moderate circulation of air, in the order of the strength of their solutions, beginning with the water and following with the weakest solution and so on. Require the subject to smell of the bottles in succession without lifting them from the table, beginning with the water, and to indicate that in which he first recognizes a characteristic odor. If the solutions stand for any length of time where they are subject to evaporation, it will be safer to prepare fresh ones before undertaking a new test. Other precautions will suggest themselves, such as the use of similar bottles, and care in filling them that none of the solution is left clinging near the mouth.

b. Test with the olfactometer. Test the sides of the nose separately. Push the odor-tube on till its end is flush with that of the glass tube, insert the bent end of the latter into the nostril, and gradually lengthen the exposed surface of the odor-tube till its odor is just discernible. Note in millimeters the length exposed.

a. Bailey and Nichols, *B*; Lombroso und Ottolenghi; Savelieff; *b.* Zwaardemaker, *A* and *C*.

58. Discriminative Sensibility for Odors. Using the double olfactometer with both odor-tubes drawn out far enough to give an unmistakable odor, but not too strong a one, say both drawn out 5 cm., find how far one or the other must be drawn out (or pushed back) to make the odor which it gives just observably stronger (or weaker) than that of the other. The test should be made with the sides of the nose separately (there is frequently a difference in sensitiveness between the two sides, due to mechanical obstruction or other cause), unless for some reason a bilateral form of experiment is desirable. Try a number of times, in half the tests smelling the weaker before the stronger, and in half the stronger before the weaker, but be careful to avoid fatigue.

59. Fatigue of Smell. *a.* Hold a piece of camphor gum to the nose, and smell of it continuously, breathing in through the nose and out through the mouth, for five or ten minutes. A very marked decrease in the intensity of the sensation will be observed, reaching perhaps even to complete loss of the odor.

b. It is important, however, to observe that fatigue for one substance does not cause obtuseness for all other substances, though it does for some. Smell of some essence of cloves and of some yellow wax, then fatigue for camphor as in *a*, and smell of the essence of cloves and of the wax again.

The odor of the wax will probably be fainter, that of the essence of cloves unaffected.

Aronsohn.

60. Combination of Odors. Experiment with the olfactometer on one side of the nose as follows. Hold against the end of the rubber odor-tube another odor-tube of wax (partly covered on the inside by a glass tube of the same size as that used in the olfactometer), in such a way that the air must pass through both to reach the nose. Then gradually increase the length of the rubber tube exposed till the odor of the wax is no longer perceived. If the experiment is carefully performed, a point may be found where the odors nearly balance. If the rubber is lengthened beyond this point, its odor overpowers that of the wax; if it is shortened, it is overpowered by that of the wax. A mixture of the odors in which both can be detected is difficult to find. Care should of course be taken to avoid fatigue.

A similar balance of odors was found by Zwaardemaker when the double olfactometer was used and the two sides of the nose received separate stimuli.

Zwaardemaker, *B.*

BIBLIOGRAPHY.

Aronsohn: Experimentelle Untersuchungen zur Physiologie des Geruchs, *Du Bois-Reymond's Archiv*, 1886, 321–357.

Bailey and Nichols: *A.* The Delicacy of the Sense of Taste, *Nature*, XXXVII., 1887–88, 557; also *Science*, 1888, 145.

B. The Sense of Smell, *Nature*, XXXV., 1886–87, 74.

Camerer: *A.* Die Grenzen der Schmeckbarkeit von Chlornatrium in wässeriger Lösung, *Pflüger's Archiv*, II., 1869, 322.

B. Die Methode der richtigen und falschen Fälle angewendet auf den Geschmackssinn, *Zeitschrift für Biologie*, XXI., 570.

CORIN: Action des acides sur le goût, *Archives de Biologie*, VIII., 1888, fasc. 1, 121–138.

GOLDSCHEIDER UND SCHMIDT: Bemerkungen über den Geschmacksinn, *Centralblatt für Physiologie*, IV., 1890, 10–12.

HAYCRAFT: The Nature of the Objective Cause of Sensation; Taste, *Brain*, X., 1887, 145–163; Smell, *Ibid.*, XI., 1888–89, 166–178.

HERMANN: Beiträge zur Kenntniss des elektrischen Geschmacks, nach Versuchen von Laserstein, *Pflüger's Archiv*, XLIX., 1891, 519–538.

HOWELL AND KASTLE: Note on the Specific Energy of the Nerves of Taste, *Studies from the Biological Laboratory, Johns Hopkins University*, IV., No. 1.

KEPPLER: Das Unətrscheidungsvermögen des Geschmacksinnes für Concentrationsdifferenzen der schmeckbaren Körper, *Pflüger's Archiv*, II., 1869, 449.

LOMBROSO UND OTTOLENGHI: Die Sinne der Verbrecher, *Zeitschrift für Psychologie*, II., 1891, 342–348.

OEHRWALL: Untersuchungen über den Geschmackssinn, *Scandinav. Archiv f. Physiol.*, II., 1890, 1–69; see also abstract by the author in the *Zeitschrift f. Psych.*, I., 1890, 141.

PASSY: Sur les minimums perceptibles de quelques odeurs, *Comptes rendus*, CXIV., 1892, 306.

RAMSEY: On Smell, *Nature*, XXVI., 1882, 187.

RITTMEYER: Geschmacksprüfungen, Inaug. Diss., Göttingen, 1885.

SAVELIEFF: Untersuchung des Geruchsinnes zu klinischen Zwecken, *Neurologisches Centralblatt*, XII., 1893, 340–345.

SHORE: A Contribution to our Knowledge of Taste Sensations, *Journal of Physiology*, 1892, 191–217.

VON VINTSCHGAU: Physiologie des Geschmackssinns und des Geruchssinns, Hermann's Handbuch der Physiologie, III., pt. 2, 143–286. For a general account of the physiology and psychology of taste and smell to 1880, and references to the earlier literature, see this work.

WUNDT: Work cited in bibliography of Chap. I., 3te Aufl., I., 411 ff.; 4te Aufl., 438 ff.

ZWAARDEMAKER: *A.* Die Bestimmung der Geruchschärfe, *Berliner klin. Wochenschrift*, XXV., 1888, No. 47, 950 (abstract of the same, *British Med. Journal*, 1888, ii. 1295); also *Lancet*, London, 1889, i. 1300.

B. Compensation von Gerüchen mittelst des Doppelreichmessers, *Fortschritte der Medicin*, VII., 1889, 721 ff.

C. Sur la norme de l'acuité olfactive (olfactie), *Archives néerlandaises*, XXV., 131–148.

D. La mesure des sensations olfactives et l'olfactomètre, *Revue scientifique*, 1889, ii. 810–812. Extract from the *Archives néerlandaises*.

CHAPTER IV.

Sensations of Hearing.

In these experiments a little knowledge of the physics of sound is presupposed — as much as would be given in an elementary course in physics. A very little knowledge of musical notation is also required, but hardly more than everybody has. No special musical skill is needed except in Exs. 70 and 93 *b*. It is also the author's belief that most persons calling themselves "unmusical," however truly they may rate themselves as performers, are very much in error as to their ability to discriminate musical sounds. The greatest difficulty in some of these experiments will be found in the continuous intrusion of outside sounds, and some even may have to be tried at night.

Sounds in General.

61. Minimal Sounds. *a.* Experiment in a large room as free as possible from noise. Let the subject be seated with his side toward the experimenter, his eyes closed, and his ear upon the other side plugged with cotton. Let the experimenter then find what is the greatest distance at which the subject can still hear the tick of a watch held at the level of his ear and on the prolongation of the line joining the two ears. This is easily done with sufficient accuracy by drawing a chalk line on the floor, marking off feet or meters and fractions upon it, and estimating by eye the point of the line directly under the watch. Try several times for each ear, both when the watch is being brought

toward the ear and when it is being carried away. The experimenter should from time to time cover the watch with his hand to discover whether or not the subject really hears, or is under illusion. For normal ears the distance found may vary from 2.5 m. to 4.5 m., and may even rise to as much as 9 m.

b. The subject should notice in this experiment the very marked intermittences of the sound when just upon the limit of audibility. It will for a few seconds be heard distinctly, and a few seconds later will as distinctly not be heard.

c. Faint sounds are apt to be underestimated. Place a sounding tuning-fork on the head and let the sound die away to almost complete extinction; then remove it. The drop to complete silence will often seem larger than the apparent intensity of the tone would justify.

On *a*, von Bezold, *A*; on *b*, Urbantschitsch, *A*; Lange; Münsterberg, *A*; on *c*, Stumpf, I., 388, who quotes from Fechner.

62. Discriminative Sensibility for Intensity of Sounds. Exact experiments on this topic are difficult to make, because of the very great difficulty of determining objectively the intensity of the sounds used. A rough determination can easily be made, however, with the sound pendulum (see chapter on apparatus). Choose a medium sound as a standard, and by the Method of Just Observable Difference explained under Ex. 24, find a sound that is just recognizably different from it. The discriminative sensibility is very much finer, apparently, when the question is not one of recognizing a difference, but of locating a sound as right or left of the median plane. Cf. Ex. 101 and Rayleigh.

Wundt, 3te Aufl., I., 364 ff.; 4te Aufl., I., 360 ff.; Stumpf, I., 345 ff.

63. Auditory Fatigue. *a.* Cause an assistant to strike once with a hammer on the floor, or to clap his hands.

With the ears open a single sound, or at most a single sound and transient echoes are heard. If, however, the ears are kept closed with the fingers till half a second or more after the stroke (the time may easily be fixed by rapid counting), the fainter echoes will be heard on the opening of the ears, like a new stroke. In the first case, fatigue from the original sound deadens the ears to the fainter echoes, though they may still be heard by attentive listening; in the second case they are more strongly heard because the closed ears are unfatigued. The sound produced by the simple opening of the ears without any objective stroke will be less if the finger is not put into the ears, but presses the *tragus* back upon the opening.

b. Strike a tuning-fork, press the stem firmly upon the mastoid process, or the crown of the head, and hold it there till the tone is no longer heard. Then instantly remove it, and after a second or two replace it upon the same spot, taking pains to press no harder than before. The fork will be heard again sounding faintly. The experiment may not succeed at first, but a few trials should not fail to show the effect.

c. Insert in the openings of the ears the ends of a rubber tube. Strike a tuning-fork and set it upon the tube at such a point that it sounds equally intense to the two ears. The sound will then probably appear to be located in the head midway between the ears — at least not nearer one than the other. After a few seconds strike the tuning-fork again, pinch the tube on one side, say the left, so as to shut off the sound from the ear on that side, set the tuning-fork at the proper place on the tube and keep it there till the sound has become rather faint. Then allow the pinched tube to open, and notice that the sound is now stronger on the left than the right and apparently located on the left. Try the experiment in reverse form, pinching the tube on the right.

Cf. later experiments on the analysis of compound tones by the fatigue method, Ex. 89 *c*.

Stumpf, I., 360–363. On *a*, Mach; on *b*, Corradi; on *c*, Urbantschitsch, *B*.

64. Inertia of the Auditory Apparatus. *a*. Inertia tending to keep the auditory apparatus out of function can be demonstrated as follows. Place the ends of a rubber tube in the ears, and set upon the middle of it a low tuning-fork sounding as faintly as possible. Notice that the sound does not reach its maximum intensity for an appreciable length of time; if the fork is barely audible, this may be as much as a second or two. Be careful not to increase the pressure of the fork upon the tube after first setting it on, for that will produce an objective strengthening of the tone; and allow an interval of several seconds between the tests so that the auditory apparatus may again come completely to rest. A tuning-fork that will preserve these minimal vibrations for some seconds, and complete freedom from distracting noises, will be found necessary for success.

b. Inertia tending to keep the auditory apparatus in function (positive auditory after-images) can be demonstrated as follows. Fasten upon the front of a rather solid pendulum a small tuning-fork, so that it shall project forward at right angles to the pendulum bar and the tines of the fork shall be vertically one above the other. On the three arms of a Y-tube attach three pieces of small rubber tubing, say quarter inch outside measurement. Those fitting on the upper arms of the Y should be of the same length, that fitting upon the stem may be of any convenient length. Insert the free end of the last mentioned tube in the outer passage of the ear, and hold the tips of the other tubes about half an inch apart, open end upward, in such a way that the tip of the tuning-fork, as the pendulum swings, will pass close over them. Strike the fork with a small rubber hammer as the

pendulum swings and notice the sound produced by the fork as it passes the ends of the tube. If a single continuous sound is heard, separate the tubes a little; if a double sound is heard, bring them together; and thus by shifting them back and forth find the place where the sounds just fuse into one. The auditory disturbance occasioned by the first pulse of sound outlasts the interval between the two, and blends with the second. Move the pendulum slowly over the end of one tube and then of the other, meantime pinching the tube over which the fork is sounding, to convince yourself that the tone is not heard at substantially the same instant in both tubes. It is possible from the rate of the pendulum and the separation of the tubes to find approximately the length of time through which the sensation persists.

c. Sometimes it is possible to get more lasting after-images and even those that are recurrent. Try with a tuning-fork struck and held a few seconds before one ear. Stop the fork by touching it, without removing it from the ear. The after-image is not very easy to observe; the lowest degree of it seems to be the transforming of faint outer noises into something qualitatively like the tone heard, or perhaps a selection of certain of those noises. The usual interval between the stimulus and the after-image is under fifteen seconds. The number of recurrences of the after-image differs in different subjects; for Stumpf, they seem to come by preference in the unstimulated ear.

Stumpf, I., 211 ff, 278; Urbantschitsch, *C*. For methods of demonstration permitting more accurate measurement of the persistence of tone, see Urbantschitsch, *C*, and Mayer, *A*.

65. Noise. Whether or not there is a distinctive sensation of noise different from that of a mass of short, dissonant, and irregularly changing tones, is yet under debate. A little attention to the noises constantly occurring, espe-

cially to their pitch, will easily convince the observer that a tonal element is present. This is striking when resonators (cf. notes on apparatus for simultaneous tones) are used, for they pick out and prolong somewhat the tones to which they correspond, but they are not indispensable. On the other hand, attention to musical tones will often discover the presence of accompanying noises.

Wundt, 3te Aufl., I., 420; 4te Aufl., I., 447 f; Stumpf, II., 497–515; Brücke; Exner; Mach, *B*, 117.

66. Silence. When circumstances promise absence of external sounds, notice that many are still present and distinct, though faintly heard. Notice also the pitch and changing character of the subjective sounds to be heard. Our nearest approach to the experience of absolute stillness is this mass of faint inner and outer sensations.

Preyer, *A*, 67–72; Stumpf, I., 380 ff.

Single and Successive Tones.

67. Highest Tones. With the apparatus at hand for the purpose, find what is the highest audible tone; i. e., if the cylinders are used, the shortest cylinder which still gives a ringing sound when struck with the hammer, or if the whistle is used, the closest position of the plunger at which a tone can still be heard beside the rush of air. If a number of persons are tested, it is not improbable that some will yet hear the tone after it has become inaudible for the rest.

Same references as Ex. 68.

68. Lowest Tones. If low-pitched tuning-forks or other vibrators are at hand, find what is the slowest rate of vibration that can yet be perceived as a tone. In some physiological laboratories electric tuning-forks or interrupters may be found that have vibration rates of twenty-five per second. Low tones can be heard from these, though they have many

overtones. The latter can be partly damped by touching the tines midway of their length with the finger, and partly avoided by bringing the ear not to the free end, but to a point somewhat nearer the handle. The determination of the lower limit of audible pitch is difficult and uncertain because of the great difficulty which observers, even those of trained ear, find in distinguishing these lowest tones from the next higher octaves. The general character of these deep tones can be demonstrated with sufficient clearness upon the contra octave (C_1–C) of a church organ, if one is accessible and tuning-forks are lacking.

Von Bezold, *B*; Wundt, 3te Aufl., I., 423; 4te Aufl., I., 450; Preyer, *A* and *D*; Stumpf, I., 263, II., 551.

69. Some Characteristics of High and Low Tones.

a. High tones are smoother than low tones. This is clear with almost all tones used in music, and particularly so with those of reed instruments. The roughness of low tones is largely due to the beating of their partials among themselves (see Exs. 86 ff. and 79 ff.) and even with the fundamental tones; the high tones having fewer audible partials are freer from it. Play the scale of any instrument from its lowest to its highest tone, or sing the ascending scale. The difference of roughness is observable also with simple tones, but only at lower pitches, and is even there less marked.

b. In spite of the generally accepted fact that high tones produce a more intense sensation than low tones of equal physical energy, high tones are more readily suppressed by stronger lower tones than *vice versa.* Place an ordinary clock at a distance of a few feet and hold close before the ear a watch. When the watch is near the ear all the ticks will be heard. As it is gradually removed, a position can be found where the watch-tick that coincides with the clock-tick will be suppressed. When both make an equal number

of ticks to a second, and one gains a little on the other, there will occur periods in which no watch-ticks are heard, and, alternating with them, periods in which all are heard. If the watch beats oftener than the clock and both run at the same rate, a single watch-tick will be lost at regular intervals. When the clock is removed, all the ticks of the watch can easily be heard at the distance used. The phenomenon can be observed when the watch is on the opposite side of the head from the clock. To demonstrate weakness of high tones in suppressing lower tones, sound together a large and a small tuning-fork on their resonance cases, e. g., c and c'', a'', or b'', sounding the first very faintly and the second as loudly as possible. The first will still be heard even when the second is brought close to the ear. In this connection compare the difficulty of analyzing the compound tones in Exs. 86 ff., also Exs. 83 *b* and 84.

c. Some high tones are particularly strengthened by the resonance of the outer passage of the ear. These generally lie between c^4 and c^5, and give to the tones of this octave a superior strength and ear-piercing quality. They may be demonstrated easily with a small piston whistle. Find by adjustment of the piston the point at which the tone is most piercing. Insert in the outer ends of the ear-passages bits of rubber tubing half an inch long (which will change the resonance of the passages, making them responsive to a lower tone) and sound the whistle again. The piercing quality will be gone and the tone appear decidedly weaker. Remove the bits of tubing and sound the whistle as before; the original quality and intensity reappear.

d. Very closely associated with the pure tonal sensations are certain of a spatial quality. Compare in this respect the sensations of the tones observed in *c* above; or, better still, those of Ex. 67 with those of Ex. 68, or any other deep tones. Play the scale through the complete compass of any instrument, keeping this quality in mind.

e. Under certain conditions, low tones seem to be located in the head, high tones outside of it. Close the ears with the fingers and have an assistant strike a low tuning-fork (e.g., 50 vibrations per sec.), and set the stem of it upon the crown of the head; notice the location. Try the same with a high fork.

f. The emotional shading of tones changes with their pitch. Recall the descriptive terms used: Deep, low, bright, sharp, acute. Play the scale, and judge of the appropriateness of these terms to match the shades of feeling that mark the tones of low, middle, and high pitch, distinguishing those that refer to pitch from those enumerated in Ex. 90, which refer to timbre.

Stumpf, I., 202–220, II., 56–59, 227; also Mach, *B*, 120 ff. On *b*, Mayer, *B*; on *c* and *f*, Helmholtz, 116, 179, and 69 ff.; on *d*, James, II., 134 ff.; on *e*, Kessel.

70. Recognition of Absolute Pitch. *a.* This experiment gives accurate results only with those of very decided musical skill, but it may be tried with any subject that knows the names of the notes. Strike various notes in different parts of the scale of the instrument and require the subject to name the note given. Record the note struck and the subject's answer. He should be seated with his back toward the experimenter, or should keep his eyes closed.

b. Pitch differences in the perceptions of the two ears. The same tone, heard first with one ear and then with the other, seems to many observers, even professional musicians, somewhat different in pitch. Take two small rubber tubes of equal size and length (e. g., quarter inch tubes, two feet long), place an end of one in the right ear, an end of the other in the left, and bring the free ends near together on the table. Then have an assistant strike a tuning-fork and

present it alternately to the ends of the tubes. The difference between the two ears is said to vary more or less from day to day and to be different in amount for tones of different pitch. Such differences may be observed by the unmusical.

Stumpf, I., 305–313, also II., index, *Höhenurteile*, for experiments on trained musicians; von Kries, *B*; on *b*, Stumpf, II., 319 f.

71. Just Observable Difference in Pitch. Test as follows with the set of mistuned forks. Let the subject pick out from the mistuned forks that which sounds to him just noticeably different from the normal fork, striking and holding them successively (never simultaneously) over a resonance bottle. If all of them seem more than just observably different, let him put the riders on the one that is next higher, and gradually lower the pitch by sliding them toward the ends of the fork till the two forks, heard successively, are just different and no more. The experimenter may then determine the error of the subject in vibrations per second approximately by counting the number of beats produced by the forks when sounded together. If the number of beats per second is less than 2 or more than 6, it will be best to get the difference in pitch with some other of the forks first, so as to avoid too slow or too rapid counting, and from that to arrive at the difference from the standard fork. Repeat the test several times, sometimes sounding the standard fork first, and sometimes that to be compared with it, and average the result. Take care to avoid fatigue. This experiment will not be refined enough for testing those of keen musical ear.

Preyer, *A*, 26 ff., *D*, 64; Stumpf, I., 296–305; Luft.

72. Differences in Pitch that are Just Recognizable as Higher or Lower. It is easier to recognize a difference than to tell its direction. Experiment as in Ex. 71, but

require the subject this time to pick out and adjust a fork that is just observably sharper or flatter than the standard.

Preyer, *A*, 28, 36. For experiments on extremely unmusical subjects, see Stumpf, I., 313–335.

73. Number of Vibrations Necessary to Produce a Sensation of Pitch. Arrange an apparatus for blowing soap-bubbles with a mixture of hydrogen and air. Blow bubbles of different sizes and touch them off with a match, either in the air, or (if proper precaution is taken to prevent the ignition of the mixed gases in the vessel and any resonance in the pipe), while still hanging. The explosion of these bubbles is supposed to produce a single sound wave. The pitch of the sounds produced cannot be accurately given, but the report of the large bubbles is distinctly deeper than that of the small ones.

Brücke; Cross and Maltby; Herroun and Yeo.

74. The Apparent Pitch of Tones is Affected by their Quality. Tones of dull and soft character seem lower in pitch than those that are brighter and more incisive. Require the subject to pick out on some stringed or reed instrument the tone corresponding to that produced by blowing across the mouth of a medium-sized bottle. Too low a note at first will generally be chosen, at least by those without special musical training. The tones should be sounded successively, not at the same time, during the test. Afterward they may be sounded together, and the pitch of the bottle determined approximately by finding with which tone of the instrument its tone makes the slowest beats (cf. Ex. 79). It should be remembered, however, that it will be possible to get beats also with tones an octave lower and an octave higher than that corresponding most nearly with the true pitch of the bottle tone.

Stumpf, I., 227–247, especially, 235–245.

75. Recognition of Musical Intervals. Cause a familiar air to be played, first in the octave of *c* and then in that of *c''* in the same or another key. Even those of no musical training will easily recognize that the air (i. e., the succession of musical intervals in fixed rhythmical relations), is the same in both cases; and any mistake or variation will be noticed as easily as if the air had been repeated at the first pitch. With the unmusical, however, the recognition is often rather of the rhythm than the intervals; try therefore a repetition of the air changing some of the intervals but preserving the original rhythm. The power of recognizing intervals is very much more highly developed in persons of musical training, but any one that can whistle a tune at one pitch and repeat it recognizably at another undoubtedly has the rudiments of interval recognition.

For exact methods of testing the accuracy of the power of recognizing intervals, see Preyer, *A*, 38–64; and Schischmánow, and the references given by them.

76. Pitch Distances. Beside the interval relations of tones, and overshadowed by them in musicians, are certain relations of separateness or distinctness or distance in pitch, which do not depend on the ratios of vibration rates. Equamusical intervals (i.e., intervals between tones that have vibration rates in a fixed ratio to each other, e.g., *C D* and *c'' d''*) do not correspond to equal pitch distances. Sound the half-tone interval *c c-sharp* through the range of the instrument, beginning in the bass and ascending. Notice the increasing distinctness and separation of the tones as the interval is taken higher and higher. For the very highest tones there is probably a decrease of separateness again. The difference is most striking, however, with intervals smaller than those in common use, e.g., with quarter or eighth tones. On the harmonical (cf. notes on apparatus) strike in succession the *c-sharp* and *d* keys in the four lower

octaves, beginning with the lowest. In this instrument the *c-sharp* key is given to another *d*, a comma, or about one-ninth of a tone, flatter than the regular *d* of the scale.

Stumpf, I., 247–253; Lorenz, and the discussion between Wundt, Stumpf, and Engel; Helmholtz, 264–265; Münsterberg, *C.*

77. The Effect of a Given Tone in a Melody depends in part on the succession of tones in which it stands. Cause a simple air, in which the same tone recurs in different successions of tones, to be played, and notice the difference in effect in the different circumstances, or simply play the ascending and descending scales.

Mach, *B*, 130–131.

78. Tones that Vary Irregularly in time and in pitch are unpleasant. Test with a piston whistle.

Simultaneous Tones.

79. Beats. When tones that are different in pitch are sounded at the same time, they mutually interfere, and make the total sensation at one instant more intense and the next instant less intense. This regular variation in intensity is called "beating." Exs. 71 and 74, where beats have been used incidentally, are a sufficient introduction to them.

a. The rapidity of beats depends on the difference in the vibration rates of the beating tones. Prepare two bottle whistles of the same size, and blow both at the same time. Slow beats will probably be heard. If not, pour a little water into one bottle (thus raising the pitch of its tone), and blow as before. Continue adding water, a little at a time, till the beats lose themselves in the general roughness of the tone. Blow the bottles separately now and then to observe the increasing difference in pitch. The same may be shown with a couple of piston whistles, if they are first

adjusted to unison, and then the piston of one or the other is slowly pushed in or pulled out.

b. Tones that are a little more or a little less than an octave apart may give beats. Try with a pair of octave-forks on resonance boxes or held over resonance bottles, one of which has been slightly lowered in pitch by weighting the prongs with wax or a bit of rubber tubing. In this case the beating-tones are the tone of the lower fork and the difference tone (see Ex. 82). Repeat the experiment on a reed instrument. In this case beats may be heard between the higher tone and the first over-tone of the lower (see Ex. 86).

c. The rate at which the roughness of rapid beats disappears, as also the rate which produces the greatest roughness, differs with the pitch of the beating-tones. Sound the following pairs of tones which have somewhat near the same difference in vibration rates per sec., namely, 33; and observe that the roughness from the beats decreases and finally disappears entirely at about the fourth pair; b' c'', c' d', e g, c e, G c, C G. The a' and c'' tuning-forks give a vanish of roughness, representing a rate of 80–88 per sec.

Helmholtz, 159–173; Stumpf., II., 449–497, especially 461–465; Mayer, *A*; Cross and Goodwin.

80. Beats Betray the Presence of very Faint Tones, both because the total stimulus is actually stronger in the phase of increased intensity, and because intermittent stimuli are themselves more effective than continuous ones.

a. Strike a pair of beating tuning-forks, and hold one at such a distance from the ear that it is very faint or quite inaudible. Then bring the other fork gradually toward the ear, and notice the unmistakable beats.

b. Strike a tuning-fork and hold it at a distance, being careful to have the fork sidewise or edgewise, not corner-

ing, toward the ear. Rotate the fork one way and the other about its long axis, and observe the greater distinctness of the tone, due in this case simply to its intermittence.

81. Beats are in general Attributed to the Tone that Receives Attention; in the absence of other determining causes, to the louder tone, to the lower tone, or to the whole mass of an unanalyzed compound tone (see introduction to Ex. 86).

a. Set two properly tuned resonance bottles about a foot apart on the table. Strike two forks that beat, and hold them over the bottles. While both are about equally intense, it is easy, by mere direction of the attention, to make the beats shift from one to the other.

b. Turn one of the forks an eighth of a turn about its long axis, which will weaken its tone, and observe that the beats seem to come from the other fork. By turning first one fork and then the other, the location of the beats may again be made to shift at pleasure. If tuning-forks on resonance boxes are at hand they may be used, and the tone of one weakened by covering the opening of the box with a bit of cardboard.

c. Warm the c' fork in any convenient way (holding it clasped in the hand will do). This will flatten it somewhat. Strike it and the c'' fork, and press the stems of both on the table at the same time; or, better, on the sounding-board of the sonometer. Observe that the beats seem to come from the c' fork unless it is very faint.

d. Tune a string of the sonometer so that its third partial (or corresponding harmonic) beats slowly with the c'' fork. (On partials and harmonics cf. Exs. 86–89.) Strike the tuning-fork, and hold it over a resonance bottle, or press its stem against the table at arm's length from the string. Then pluck the string and attend to its tone; the beats may

seem to affect the whole compound tone of the string. But this will not happen if the tone of the string is analyzed, or if the attention is directed to the fork. The same may be tried on the piano by picking out from the mistuned c'' forks one that beats slowly with c'' on the piano. Strike the *f* key and hold it down; strike the fork, and observe the beats as before. Cf. Ex. 69 *a*.

Stumpf, II., 489–497.

82. Combination Tones: Difference Tones.[1] When two tones are loudly sounded at the same time they produce by their combination other tones, one of a pitch represented by the difference of the vibration rates of the two original or generating tones, and one of a pitch corresponding to their sum. The existence of the summation tones has been disputed, and they are hard to hear. The difference tones, however, are easy to hear, at least when they are considerably lower in pitch than the generators, when the latter are loud and sustained, and when they make a consonant interval — though the last is not essential. A loud difference tone may itself take the part of a generator and produce yet another difference tone — a difference tone of the second order — and so on, though difference tones of higher orders are heard with difficulty even by skilled observers. Difference tones are hard to hear on the piano and similar stringed instruments because of the rapid decline in the strength of the generators. The difference tones are sometimes called Tartini's tones, after an early observer of them.

a. Repeat Ex. 79 *a*, continuing to pour water into one of the bottles till the difference tone appears. At first the roughness of the beats and the difference tone may both be

[1] König distinguishes between "difference tones" and "beat tones." Both tones, however, generally have the same pitch, and the older term for them has here been retained; strictly speaking, however, the "difference tones" heard in these experiments are "beat tones."

heard at once. Try the same with the piston whistles, first setting them at unison, and then slowly pushing the piston of one in or out while blowing rather hard. The beats will almost immediately give place to a low difference tone which may be heard ascending through several octaves before becoming indistinguishable from the generators. The double warning whistles used by bicyclists give a fine difference tone, to which indeed they owe their deep and locomotive-like quality.

b. Difference tones are strong on reed instruments. Press the adjacent white keys of a parlor organ, or the harmonical, by twos, beginning at *c* and going up a couple of octaves. If there is difficulty in hearing the difference tone, sound the upper tone intermittently and listen for the difference tone at the instant of pressing the key.

c. Sound c'' and d'' which should give C as a difference tone (594—528=66). Sound also d'' and e'' which should give the same (660—594=66). If, however, the tuning is inexact, as it is intentionally in the tempered tuning of keyed instruments, these difference tones will be somewhat different and may be heard to beat with each other when c'', d'' and e'' are sounded at once. Notice that these beats are not heard when the tones are sounded in pairs. On the harmonical this difference may be brought about by sounding one of the tones flat by pressing its key only a little way down. The same thing may be shown with three piston whistles blown at once, by a little careful adjustment of the pistons.

d. In the case of reed instruments the difference tones probably owe part of their intensity to the vibrations of the air in the wind chest. When two whistles are blown by one person something of the same kind may happen. In order to make a clean experiment, have the whistles blown by two assistants, or observe the difference tones from tuning-forks.

e. The location of difference tones. The location of these tones is sometimes influenced by the location of their generators, but under favorable circumstances they seem to arise in the ears or even in the head. This is strikingly the case, both for the blower and the listeners, with the difference tones produced with the piston whistles. Cf. Ex. 69 *e.*

Helmholtz, 152–159; Stumpf, II., 243–257; König; Preyer, *C* and *D*; Hermann.

83. Blending of Tones. The degree to which tones blend with one another differs with the interval relation of the tones taken. It is, according to Stumpf, greatest with the octave, less with the fifth, less again with the fourth, slight with the thirds and sixths, and least of all with the remaining intervals.

a. Try on the instrument the extent to which the tones forming these intervals blend, also those forming intervals greater than the octave: double octave, twelfth, etc.

b. The blending in case of the octave is so complete under favorable circumstances as to escape the analysis of trained ears. Use two tuning-forks, one an octave higher than the other, on resonance cases or held over resonance bottles. Sound the forks, first the higher, then the lower. For a while the higher fork will be heard sounding in its proper tone, but by degrees it will become completely lost in the lower, and a subject with closed eyes will be unable to say whether or not it yet sounds. Cf. Ex. 69 *b.* Stop the lower fork, or remove it from its resonance bottle, and notice that the higher is still sounding. Notice the change in timbre (cf. Ex. 90) produced by the stopping of the higher fork — something like the change from the vowel O to the vowel U (oo).

On *a*, Stumpf, II., 127–218, especially 135–142; for his experiments on the unmusical confirming his grades of blending, 142–173. On *b*, Stumpf, II., 352–358, and Helmholtz, 60–61.

84. Analysis of Groups of Simultaneous Tones. Ease of analysis depends on a number of conditions, among others on the following.

a. Analysis is easier for tones far distant in the scale. Compare the ease of recognizing the sound of the c'' fork when c' and c'' are sounded together, with that of recognizing c''' when sounded with c'. Compare also the ease of distinguishing c' and a' with that of distinguishing c' and a''.

b. Analysis is made easier by loudness in the tone to be separated. Repeat Ex. 83 *b*, sounding the c' faintly, the c'' strongly. Little difficulty will be found in keeping the latter distinct.

c. Analysis is easier when the tones make intervals with little tendency to blend. Compare the ease of analysis of c' c'' and c' a' or a' c''. Also notice that the addition of d'' (octave of d', fifth of g', fourth below g'') to the chord g d' g' g'' produces a less striking change than the addition of b' (major third of g', minor sixth below g'') to the same chord.

d. Analysis is easier with sustained than with short chords. Repeat the last experiment, making the chords very short, and notice that the difference made by inserting either d'' or b' is less marked. Cf. also Ex. 100.

Stumpf, II., 318–361; also his experiments, 362–382.

85. The Lower Tone of a Chord Fixes the Apparent Pitch of the Whole. *a.* Repeat Ex. 83 *b*, and notice that when the c' fork is stopped, the tone appears to jump upward an octave in pitch (i.e., it takes the pitch of the c'' still sounding); but when the c'' fork is removed, the quality of the tone is changed, but not its pitch.

b. Strike the chord C c'' e'' g'' or G e' g' c'', and compare the effect upon the pitch of the whole mass of tone produced by omitting C or G alone with that of omitting any one or all three of the higher tones. See also the function

of the lowest partial of a compound tone in fixing the pitch, noticed below.

Stumpf, II., 383-392.

86. Compound Tones. Almost all tones heard, and indeed all those used in music, are not simple tones, but compound. The tone given by the C string of a piano is made up of at least C, c, g, c', e' and g', and generally other tones. The lowest tone of the group gives the pitch attributed to the whole, and is known as the *fundamental*, the other tones as *over-tones*. In another way of naming them, the component tones are all *partial tones* or *partials*, the fundamental being called the *first* or *prime partial*, the next higher the *second partial* and so on. The *first* over-tone is thus the *second* partial tone, the *second* over-tone the *third* partial, and in general the same tone receives as a partial tone a number one higher than as an over-tone. The vibration rates of the partial tones of a compound are generally once, twice, three times, four times, the rate of the fundamental, and so on. In some cases, however, e.g., in bells and tuning-forks, one or more of the partial tones may have a vibration rate not represented in this series, and discordant with the fundamental tone. In what follows, the regular series of partial tones is meant except where the contrary is specified.

Partial Tones. If resonators are at hand, the demonstration of the partial tones will be easy. Sound on a stringed or reed instrument the tones to which the resonators are tuned, and notice that they resound strongly to these tones and less strongly or not at all to other tones adjacent in pitch. Then sound the tone to which the largest of the resonators is tuned (or a tone an octave lower), and try the resonators in succession. Notice that others also resound (at their own proper pitch), thus betraying the presence of the tones to which they are tuned, and

thus the composite character of the tone under examination. Which resonators will "speak" will depend on the instrument used; reed instruments give a long and perfect series, piano and stretched wires a perfect series generally as far as the ninth or tenth partial, and stopped organ-pipes a short series. If difficulty is found in knowing when the resonator is resounding, it will be found useful to apply it to the ear intermittently, alternating, for example, two seconds of application with two seconds of withdrawal.

87. Partial Tones: Analysis by indirect means. *a.* By sympathetic vibration. This succeeds especially well with the piano. Press the *c* key and hold it down so as to leave its strings free to vibrate; then strike the *C* key forcibly, and after one or two seconds release it. The *c* strings will be found to be sounding. Repeat, trying *c-sharp* or *b* instead of *c;* they will be found not to respond. Repeat the experiment, substituting g, c', e', g', or c''; all will be found to respond but in lessening degrees. Other keys between *C* and c'' may be tried but will be found in very faint vibration, if at all.

b. By beats. This will succeed best with a reed instrument, e. g., a parlor organ or the harmonical. By pressing the keys of the instrument only a little way down, any of its tones may be sounded a little flatter than its true pitch and so in condition to beat with any other tone having that true pitch. Sound at this flattened pitch the over-tones of *C* in succession while *C* is sounding, and notice the slow beats that result. For verification sound other tones not over-tones of *C*, and notice that the beats when present are much more rapid.

88. Partial Tones: Direct analysis without special apparatus. The directions given here apply to the sonometer, but will be readily adaptable to any stringed instrument in which

the strings can be exposed. It is easier to hear any partial tone in the compound, if the partial is first heard by itself, and then immediately in combination with the rest. On strings this is easily done by sounding the partials as "harmonics." Pluck the string near one end (say about one-seventh of the length of the string from the end), and immediately touch it in the middle with the finger or a camel's-hair brush. The fundamental will cease to sound and its octave (the second partial) will be left sounding, as a "harmonic." With it sound also other even-numbered partials, but less strongly. Pluck as before, and touch the string at one-third its length; the third partial will now sound out strongest, with the sixth, ninth, etc., more faintly. Thus by plucking the string and touching it respectively at one half, one third, one fourth, one fifth, one sixth, one seventh, one eighth, one ninth, and one tenth its length from the end, the series of tones corresponding to the 2d, 3d, 4th, 5th, 6th, 7th, 8th, 9th, and 10th partials can be heard, each in large measure by itself. In getting the higher "harmonics" it will be found better to pluck nearer the end than one seventh, and in no case should the string be plucked at the point at which it is presently to be touched. (Cf. Ex. 90 *b*.)

To hear the partial tones when sounding in the compound, proceed as follows. Sound the required tone as a "harmonic," and then keeping the attention fixed on that tone, stop the string and pluck it again, this time letting it vibrate freely. The tone just heard as a "harmonic" will now be heard sounding with the rest as a partial. When the partial is thus made out, verify the analysis by touching the string again and letting the tone sound once more as a "harmonic." Try in this way for the partials up to the tenth; first for the 3d, 5th, and 7th, afterward for the 6th, 4th, and the 2d, which is the most difficult of all. It is said that analysis

is easier at night (not alone on account of the greater stillness) and when one ear is used, and that certain positions of the head favor certain partials.

89. Partial Tones: Direct analysis without apparatus. Certain parts of a compound tone are sometimes so separated by their dissonance, intensity, or pitch that they stand out with striking clearness.

a. Strike a tuning-fork on a hard surface, and observe the high, ringing, dissonant partials. They fade out before the proper tone of the fork, and are heard best when the fork is not held near the ear.

b. As the tone of a string is allowed to die away of itself, different partial tones come successively into prominence. Try with a low piano string, keeping the key pressed down while the sound fades, or with the sonometer. Something of the same kind, but less marked, happens in the dying away of a low tone on a reed instrument when the air is allowed to run low in the bellows.

c. When a tone is sounded continuously for some time on a reed instrument with one of the keys clamped down, different partials come successively into prominence, either through varying fatigue or the wandering of attention.

Helmholtz, 36–65; Stumpf, II., 231–243; see also the index under *Obertöne;* Mach, *A*, 58, *B*, 127.

90. Timbre. The peculiar differences in quality of tones (distinct from pitch and intensity) which are known as differences in timbre (tone-color, clang-tint, *Klangfarbe*), are due largely to differences in the number, pitch, and intensity of the partial tones present. Compare in this respect the dull-sounding bottle-tones or the tones of tuning-forks held over resonance bottles, and the more brilliant tones of a reed or stringed instrument; the first are nearly simple tones, while the second have strong and numerous over-tones.

a. Notice the difference in quality between the tone given by a tuning-fork held before the ear and that given by the same fork when its stem is pressed upon the table. In the second position the over-tones are relatively stronger.

b. Notice the differences in quality in the tone of a string when it is plucked in the middle, at one third its length and at about one seventh. When plucked in the middle, many odd-numbered partials are present, and the even-numbered partials are either absent or extremely faint, and the tone is hollow and nasal; when plucked at one third, the third, sixth, and ninth partials are wanting, and the tone is hollow, but not so much so as before; when plucked at one seventh all the partials up to the seventh are present. For their theoretical intensities, cf. Helmholtz, 79.

c. Try also plucking very near one end, plucking with the finger-nail and striking the string with a hard body, e. g., the back of a knife-blade; all these bring out the higher and mutually discordant partials strongly, and produce a brassy timbre.

Helmholtz, 65–119; Stumpf, II., 514–549.

91. In Successive Chords the Whole Mass of Tone seems to move in the same direction as the part that changes most. Strike in succession the chords *e′ g′-sharp b′ e″*, *a a′ c″-sharp e″*, or *a c′ e′ c″*, *a c′ f′ c″*. If the attention is directed to the bass in the first example and to the alto in the second the whole mass of tone will appear to descend in the first case and to ascend in the second. If the attention is kept on the soprano part the illusion will not appear, as also when the observer examines his sensations critically. Cf. also Ex. 81 *d*, where beats of a partial tone are attributed to the whole compound tone.

Mach, *B*, 126–127; Stumpf, II., 393–395.

92. Simultaneous Tones interfere somewhat with one another in Intensity.

a. Play the groups of notes numbered 1, 2, and 3 and observe the slight increase in the apparent intensity of the remaining tones as one after another drops out, making 1 sound like 1a, 2 like 2a, and so on. On the piano it will be well to play the notes an octave or two lower than they are written.

b. Play the notes marked 4, and notice that the increase of loudness seems to affect the note (highest or lowest) that receives particular attention, making the effect in one case like 4*a*, in the other like 4*b*.

Mach, *B*, 126; Stumpf, II., 418–423.

93. Consonant and Dissonant Intervals. *a*. The consonant intervals within the octave are the unison, octave, fifth, fourth, major sixth, major third, minor third, and minor sixth. They will be found to decrease in smoothness about in the order given. Try them beginning with the octave and at *c*, as follows: *c* c', *c g*, *c f*, *c a*, *c e*, *c e-flat*, *c a-flat*. Try the last four intervals also in the octave of c'' or c''' and notice that they are less rough than when taken in the

octave of *c*. Any other intervals within the octave are dissonant. Try *c c-sharp, c d, c b, c b-flat, c f-sharp.* The roughness is due to beating partial tones and in general is greater when these stand low in the partial tone series and are loud, and when they lie within a half-tone of each other. Work out for the tones of several of the intervals the series of partial tones up to the eighth. In general the extension of intervals into the second octave (taking the higher tone an octave higher or the lower tone an octave lower) does not change the fact of consonance or dissonance, though it may change the relative roughness.

b. Those fitted by musical training to pronounce upon questions of consonance and dissonance hold that dissonance can be perceived between simple tones under conditions that exclude beats, and that consonance is something more than the smooth flowing of tones undisturbed by beats. The test is easy to make. Hold tuning-forks making the interval to be tested one before each ear, and if there are beats, carry the forks far enough away in each direction to make the beats inaudible. Only those of musical ear, however, can pronounce upon the result.

Helmholtz, 179–197; Stumpf, II., 470, 460; Wundt, 3te Aufl., I., 439, II., 47 ff; Mach, *B*, 129–130; Preyer, *D*, 44 ff.

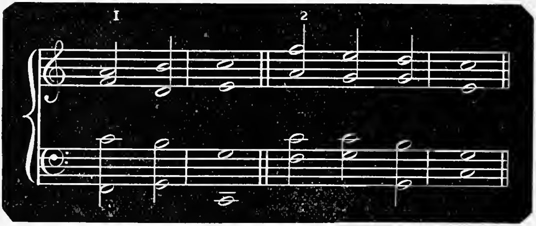
94. Consonant and Dissonant Chords. In order to form a consonant chord, all the intervals among the tones must also be consonant. The only chords of three tones which fulfil this condition within the octave are represented by the following: Major *c e g, c f a, c e-flat a-flat,* minor *c e-flat g, c f a-flat, c e a.* Try these and for comparison any other chord of three tones having *c* for its lowest tone.

Helmholtz, 211 ff.; Wundt, 3te Aufl., II., 61, 63 ff.

95. Major and Minor Chords. Compare the chords *c″ e″ g″* and *c″ e″-flat g″*. This unmistakable difference in effect

depends in part at least on the fact that in the major chord the difference tones of the first order are lower octaves of *c''* itself, while in the minor chord one difference tone is not such at all, and if taken in the same octave with the chord would be highly dissonant. For the major chord, when taken in the octave of *c''*, the difference tones are *c* and *c''*, for the minor chord *c e-flat, A-flat.* Try on a reed instrument the difference tones generated by *c'' e'', e'' g'', c'' e''-flat, e''-flat g''*, first separately; and then, while *c''* and *g''* are kept sounding strike *e''* and *e''-flat* alternately.

Helmholtz, 215–217; Stumpf, II., 335, 376 ff.; Wundt, 3te. Aufl., II., 61 ff., 67 ff.



96. Cadences. Modern music requires the prominence of the key note or tonic and of the chord in which it holds the chief place at the beginning of a piece of music and at the end. The feeling of the appropriateness of this close, and especially of the succession of chords in the cadences above, can hardly fail to appeal even to the unmusical.

Helmholtz, 293.

97. The Absolute Time Relations of music have much to do with its emotional effect. Have a familiar piece of music played in its proper time, then very slowly and very rapidly.

Binaural Audition and the Location of Sounds.

98. Unison Tones Heard with the Two Ears. *a.* Strike a pair of unison forks that will sound equally loud and vibrate an equal length of time, and hold one before each ear, three or four inches away; a single tone of rather indefinite location will be heard. As the forks are brought nearer, their tone seems to draw by degrees toward the median plane; and when they are very loud and near, the tone may seem to be in the head. Return the forks to their first position and then move one a little nearer or a little farther away, and notice that the sound moves to the side of the nearer fork. When the difference in distance has become considerable that fork alone will be heard.

b. Bring the forks again into the positions last mentioned — one near and one far, (or better, place one fork on a rubber tube one end of which has been inserted in the opening of the ear and hold the other fork before the other ear), and then with the free or more distant fork make slow rhythmical motions toward and away from the ear, or rotate the fork slowly about its long axis, attending meantime to the fork on the other side. Alternate variations in the intensity of the tone of this fork corresponding to the approach and recession of the other and apparently unheard fork can be observed.

c. Repeat *b* and notice that when the changes in intensity are considerable there is a simultaneous shifting of the place of the tone, towards the median plane when the tone grows stronger, and away when it grows fainter. These changes of place are, however, less marked than the changes in intensity and those accompanying slight changes in intensity generally escape observation.

Schaefer, *B*; Thompson; Urbantschitsch, *B*.

99. Beats Heard with Two Ears. *a.* Operate as in Ex. 98 *a*, with forks beating three or four times a second.

b. Try with a pair of very slow beating forks (once in two or three seconds). Notice a shifting of the sound from ear to ear corresponding to the rate of beating.

c. Try again with a pair of rapid beating forks (twenty or thirty a second), and notice that the beats are heard in both ears.

Schaefer, *A*, *B*, and *C*; Thompson; Cross and Goodwin.

100. Difference of Location Helps in the Analysis of Simultaneous Tones. Compare the ease with which the tones of a pair of octave forks are distinguished when the forks are held on opposite sides of the head with the difficulty of analysis in Ex. 83 *b*.

Stumpf, II., 336, 363.

101. Judgments of the Direction of Sounds. These depend in general on the relative intensity of the sounds reaching the two ears, but there is pretty good reason to believe that other factors co-operate and that tolerably correct judgments, both as to distance and direction, can sometimes be made from the sensations of one ear.

a. Let the subject be seated with closed eyes. Snap the telegraph snapper at different points in space a foot or two distant from his head, being very careful not to betray the place in any way, and require him to indicate the direction of the sound. Try points both in and out of the median plane. Observe that the subject seldom or never confuses right and left but often makes gross errors in other directions. Constant tendencies to certain locations are by no means uncommon.

b. Have the subject hold his hands against the sides of his head like another pair of ears, hollow backward, and try the effect upon his judgment of the direction of the snapper.

c. Find approximately how far the snapper must be moved vertically from the following points in order to make a just observable change in location: on a level with the ears in the median plane two feet in front; opposite one ear, same distance; in the median plane behind the head, same distance. Find the just observable horizontal displacements at the same points. A convenient way of measuring these distances is to clamp a yard-stick to a retort-stand, bring it into the line along which measurements are to be made and hold the snapper over the divisions of the stick. Snap once at the point of departure, then at a point a little way distant in the direction to be studied; again at the first point, so that the subject may keep it in mind, and then at a point a little more distant, and so on till a point is finally found which the subject recognizes as just observably different. Repeat, alternating snaps at the point of departure with those at a greater distance than that just found, decreasing the latter till a point is found where the directions can be no longer distinguished. Make a number of tests each way and take their average.

d. Continuous simple tones are very difficult to locate. Place a tuning-fork on its resonance case at some distance in front of the subject (seated with closed eyes), another at an equal distance behind him. With the help of an assistant strike both forks, and after a little have one of them stopped and the mouth of its resonance box covered. Require the subject to say which has been stopped. His errors will be very frequent. Compare with this his ability to distinguish whether a speaker is before or behind him.

On *a*, Preyer, *B*; von Kries, *A*; on *c*, Münsterberg, *B*; on *d*, Rayleigh.

102. Intercranial Location of Sounds. *a.* Sounds originating outside the head are not located in the head when heard with one ear. Hold a loud-sounding tuning-fork

near the ear, or place it on a rubber tube, one end of which is inserted in the opening of the ear, and notice that the sound when strong may be located in the ear, but does not penetrate farther. Insert the other end of the tube in the opening of the other ear and repeat. The tone, if loud, will appear to come from the inside of the head. Removing and replacing the fork several times will help to give definiteness to the location.

b. Repeat the experiment, but use a fork sounding as faintly as possible (e.g., set in vibration by blowing smartly against it), and notice that the location, when a single ear receives the sound, is not so clearly in the ear, and, when both receive it, not so clearly in the head, perhaps even outside of it. Cf. also Ex. 103 *b*. Both *a* and *b* may also be made with beating tones instead of a single one. See also Ex. 69 *e*.

Schaefer, *B*.

103. Location of the Tones of Tuning-forks Pressed against the Head. *a.* Strike a large and loud-sounding tuning-fork, and press its stem against the vertex. The tone will seem to come from the interior of the head, chiefly from the back. While the fork is in the same position, close one of the ears with the finger, not pressing it too tight; the sound will immediately seem to concentrate in the closed ear. Have an assistant manage the fork, and close the ears alternately. Something of the same kind happens when a deep note is sung; close first one ear and then both, and notice the passage of the tone from the throat to the ear and finally to the middle of the head.

b. Have an assistant manage the fork, and close both ears. Notice that when the fork is pressed on so as to make the tone loud the intercranial location is exact, but when the pressure is relaxed and the tone is faint the location tends to be extracranial.

c. Try setting the fork on other places than the vertex. Notice that in the occipital and parietal regions the sound appears in the opposite ear, though closing the ear as in *a* may bring it back to the same side as the fork.

d. Take a long pencil in the teeth like a bit and rest the stem of a vibrating tuning-fork vertically on it near one end and close the ear on the other side; the sound will seem to be located in the closed ear. Then gradually tilt the fork backward toward a horizontal position, keeping it in contact with the pencil, till its tip is opposite the open ear. The tone will change its place from the closed to the open ear.

On *a* and *b*, Schaefer, *B* and *C*; on *c*, Thompson.

BIBLIOGRAPHY.

BRÜCKE: Ueber die Wahrnehmung der Geräusche, *Wien., Sitzb. 3te Abth.*, XC., 1884, 199–230.

VON BEZOLD: *A.* Schuluntersuchungen über das kindliche Gehörorgan, *Zeitsch. f. Ohrenheilkunde*, XIV., 1884–85, and XV., 1885–86; also in English translation in the *Archives of Otology*, XIV. This paper gives the results of numerous tests on Munich school-children, not only with the watch but also with the acoumeter of Politzer and with whispered speech.

B. Einige weitere Mitteilungen über die kontinuierliche Tonreihe, insbesondere über die physiologische obere und untere Tongrenze, *ibid.*, XXIII., 1892, 254–267; also in English translation, *Archives of Otology*, 1893, 216–225.

CORRADI: Zur Prüfung der Schallperception durch die Knochen, *Archiv für Ohrenheilkunde*, XXX., 1890, 175–182. Review with extract in the *Zeitschrift für Psychologie*, II., 1891, 124.

CHARPENTIER: Recherches sur l'intensité comparative des sons d'après leur tonalité, *Archives de physiologie, normale et pathologique*, 1890, No. 3, 496–507.

CROSS AND GOODWIN: Some Considerations regarding Helmholtz's Theory of Consonance, *Proceedings of the American Academy of Arts and Sciences*, 1891–92, 1–12.

CROSS AND MALTBY: On the Least Number of Vibrations Necessary to Determine Pitch, *ibid.*, 222–235.

DOCQ: Recherches physico-physiologique sur la fonction collective des deux organs de l'appareil auditif. *Mémoires couronnés de l'Académie royale de Belgique*, XXXIV., 1870.

EXNER: Zur Lehre von den Gehörsempfindungen, *Pflüger's Archiv*, XIII., 1876, 228–253.

HELMHOLTZ: Sensations of Tone, English translation by Ellis, 2d Ed., London, 1885. This is the great classic of the subject.

HENSEN: Physiologie des Gehörs, Hermann's Handbuch der Physiologie, III., pt. 2, 1–137.

HERMANN: Zur Theorie der Combinationstöne, *Pflüger's Archiv*, XLIX., 1891, 499–518.

HERROUN AND YEO: Note on the Audibility of single Sound Waves and the Number of Vibrations necessary to produce a Tone, *Proc. Royal Soc.*, L., No. 305, 1892, 318–323.

JAMES: Principles of Psychology, New York, 1890.

KESSEL: Ueber die vordere Tenotomie, *Archiv für Ohrenheilkunde*, XXXI., 1891, 131–143, Reviewed, *Zeitschrift für Psychologie*, II., 1891, 398.

KÖNIG: Quelques expériences d'acoustique, Paris, 1882.

VON KRIES: *A.* Ueber das Erkennen der Schallrichtung, *Zeitschrift für Psychologie*, I., 1890, 235–251, 488.
B. Ueber das absolute Gehör, *Ibid.*, III., 1892, 257–279.

LANGE: Beiträge zur Theorie der sinnlichen Aufmerksamkeit und der activen Apperception, *Wundt's Philosophische Studien*, IV., 1888, 390–422.

LORENZ: Untersuchungen über die Auffassung von Tondistanzen, *Wundt's Philos. Studien*, VI., 1890, 26–103.

LUFT: Ueber die Unterschiedsempfindlichkeit für Tonhöhen. *Wundt's Philos. Studien*, IV., 1888, 511–540.

MACH: Works cited with same letters in bibliography of Chap. II.

MAYER: *A.* Researches in Acoustics, *Amer. Jour. Science*, 3d Ser. VIII., 1874, 241–255, IX., 1875, 267–269, also *Phil. Mag.*, 4th Ser. XLIX., Jan.–June, 1875, 352.

B. Researches in Acoustics, No. VIII., *Amer. Jour. Sc.*, 3d Ser. XII., 1876, 329–336, also *Phil. Mag.*, Ser. 5, II., July–Dec., 1876, 500–507.

MÜNSTERBERG: *A.* Schwankungen der Aufmerksamkeit, *Beiträge zur experimentellen Psychologie*, Heft 2, 1889, 69–124.

B. Raumsinn des Ohres, *Ibid.*, 182–234.

C. Vergleichung von Tondistanzen, *Ibid.*, Heft 4, 1892, 147–177.

PREYER: *A.* Ueber die Grenzen der Tonwahrnehmung, Sammlung physiologischer Abhandlungen, I., Jena, 1877, 1–72.

B. Die Wahrnehmung der Schallrichtung mittelst der Bogengänge, *Pflüger's Archiv*, XL., 1887, 586–622.

C. Ueber Combinationstöne, *Wiedemann's Annalen*, XXXVIII., 1889, 131–136.

D. Akustische Untersuchungen, Sammlung physiologischer Abhandlungen, II., Jena, 1882, 175–244.

RAYLEIGH: Our Perception of the Direction of a Source of Sound, *Nature*, XIV., 1876, 32. See also Acoustical Observations, *Phil. Mag.*, Ser. 5, III., Jan.–June, 1877, 456–458.

RUTHERFORD: A Lecture on the Sense of Hearing, delivered before the British Association at Birmingham on Sept. 6, 1886, *Lancet*, 1887, i. 2–6.

SCHAEFER: *A.* Ueber die Wahrnehmung und Lokalisation von Schwebungen und Differenztönen, *Zeitschrift für Psychologie*, I., 1890, 81–98.

B. Zur interaurealen Lokalisation diotischer Wahrnehmungen, *Ibid.*, I., 1890, 300–309.

C. Ein Versuch über die intrakranielle Leitung leisester Töne von Ohr zu Ohr, *Ibid.*, II., 1891, 111–114. See also discussion of Schaefer, Scripture and Wundt, *Ibid.*, IV., 348; V., 397; and *Wundt's Philos. Studien*, VII., 630; VIII., 638, 641.

SCHISCHMÁNOW: Untersuchungen über die Empfindlichkeit des Intervallsinnes, *Wundt's Philos. Studien*, V., 1889, 558–600.

STUMPF: Tonpsychologie, Leipzig, 1883 and 1890. This work of Stumpf's is by far the most complete upon the Psychology of Tone. The two volumes so far published (the work is to be complete in four) cover the psychology of successive and of simultaneous tones.

THOMPSON, SYLVANUS P.: *A.* On Binaural Audition, *Phil. Mag.*, Ser. 5, IV., July–Dec., 1877, 274–276; VI., July–Dec., 1878, 383–391; XII., July–Dec., 1881, 351–355.

B. On the Function of the Two Ears in the Perception of Space, *Ibid.*, XIII., Jan.–June, 1882, 406–416.

URBANTSCHITSCH: *A.* Ueber eine Eigentümlichkeit der Schallempfindungen geringster Intensität, *Centralblatt f. d. med. Wissens.*, 1875, 625–628.

B. Zur Lehre von der Schallempfindung, *Pflüger's Archiv*, XXIV., 1881, 574–595.

C. Ueber das An- und Abklingen acustischer Empfindungen, *Ibid.*, XXV., 1881, 323–342.

WUNDT: Work cited in bibliography of Chap. I., 3te Aufl., I., 415 ff., II., 42 ff.; 4te Aufl., I., 443 ff.

On the physics and physiology of sound, reference may be made, in addition to the works already mentioned, to Tyndall, On Sound; Blaserna, Theory of Sound in its Relations to Music; Zahn, Sound and Music; and Taylor, Sound and Music. The last is very simple and untechnical, and is perhaps the best for those approaching the subject for the first time.

For the Stumpf-Wundt discussion on pitch distances consult the following: Stumpf, *Zeitschrift für Psychologie*, I., 1890, 419; II., 1891, 266, 426, 438; Engel, *Ibid*, II., 1891, 361; Wundt, *Philos. Studien*, VI., 1890–91, 605; VII., 1891, 298, 633; also Münsterberg, *C*, above.

CHAPTER V.

The Mechanism of the Eye and Vision in General.

THE mechanism of the eye accomplishes two things: the projection of a sharp image on the retina, and the ready shifting of the eye so as to bring successive portions of the image into the best position for seeing. To the study of these mechanisms and other physiological phenomena of importance for the psychology of vision, this chapter is devoted.

THE RETINAL IMAGE AND ACCOMMODATION.

104. The Retinal Image. This is easily seen in the unpigmented eye of a pink-eyed rabbit.

a. Chloroform the rabbit, remove the eyes, and mount them in clay for readier handling. The mounting is done as follows: Make a thick ring of clay with an internal diameter a little greater than that of the cornea of the rabbit's eye; place the eye, cornea downward, in the ring; lay a similar ring upon it to keep it in place, and press the edges of the rings together. The eye can now be handled easily and turned in any direction. Turn the cornea toward the window, and observe, from behind, the inverted image on the retina. Bring the hand into range and move it to and fro; observe that the image of distant objects is more distinct than that of the hand. The dead eye is adjusted for distant vision. If convex and concave lenses are at hand (spectacle lenses will answer), bring them before the eye, and observe that the effect upon the

retinal image is similar to that seen subjectively when they are held before the observer's own eye, provided that that is normal.

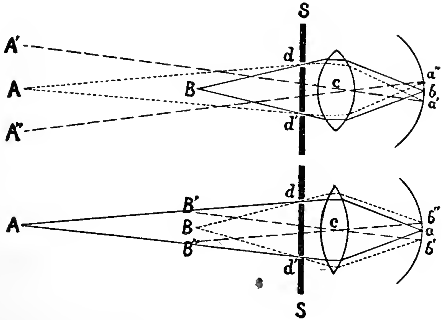
Reverse the eye, holding it retina side toward the window, and observe the radiating and circular fibres of the iris. The eye must be fresh, for if long removed it loses its transparency.

105. Accommodation. The sharpness of the retinal image depends on the adjustment of the crystalline lens, which must be such as to focus upon the retina the light from the object under regard. The lens must be thicker and rounder for near objects, thinner and flatter for more distant ones. These adaptations of the eye are known as *Accommodation.* The changes in the clearness of the retinal image are easy to observe subjectively. Hold up a pin or other small object six or eight inches away from the eyes. Close one eye and look at the pin with the other. The outline of the pin is sharp, but the outlines of things on the other side of the room behind it are blurred. Look at these, and the outline of the pin becomes blurred. Notice the feeling of greater strain when looking at the nearer object. The experiment is somewhat more striking when the nearer object is a piece of veiling or wire gauze, and the farther, a printed page held at such a distance that it can just be read.

On this and the next two experiments, see Helmholtz, *A*, 112–118, Fr. 119–126 (90–96).

106. Scheiner's Experiment. *a.* Pierce a card with two fine holes separated by a less distance than the diameter of the pupil, say, a sixteenth of an inch. Set up two pins in corks, distant respectively eight and twenty inches from the eye in the line of sight; close one eye, and holding the card close before the other with the holes in the same hori-

zontal line, look at the nearer pin; the farther pin will appear double. Look again at the nearer pin, and while looking, cover one of the holes with another card; one of the images of the farther pin will disappear — the left when the left hole is covered, and the right when the right is covered. Look at the farther pin or beyond it; the nearer pin appears double. Repeat the covering; closing the left hole now destroys the right image, and covering the right destroys the left.



Why this should be so will be clear from the diagrams above. The upper diagram illustrates the course of the rays of light when the eye is accommodated for the nearer pin; the lower diagram when it is accommodated for the farther pin. A and B represent the pins; S and S the pierced screen; d and d' the holes in the screen; c and c the lens; a' b a'' and b' a b'' the retinæ; A', A'', B' and B'', the positions of the double images. The solid lines represent the course of the rays from the pin that is accommodated for; the lines of short dashes, the course of the rays from the other pin;

the lines of long dashes, the *lines of direction*; i.e., approximately those giving the direction in which the images appear to the observer. In the upper diagram the rays from B are focused to a single retinal image at b, while those from A, being less divergent at first, are brought to a focus nearer the lens, cross over and meet the retina at a' and a'', and, since each hole in the screen suffices to produce an image, cause the pin to appear double. Its two images are referred outward as all retinal images are, along the lines of direction (which cross a little forward of the back surface of the lens, in the *crossing point of the lines of direction*), the right retinal image corresponding with the left of the double images and *vice versa*. If now the right hole (d) in the screen be closed, the left retinal image and the right double image disappear. The case of accommodation for the farther pin will be clear from the lower diagram, if attention is given to the dotted and dashed lines. It will also be easy to explain why moving the card when looking through a single pin-hole causes apparent movements of the pin not accommodated for, and why in one case the movement seems to be with the card, and in the other case against it.

b. Stick the pins into the corks so that they shall extend horizontally, and examine them with the card held so as to bring the holes one above the other.

c. Arrange the holes thus: . ˙. and observe that the triple image of the nearer pin (when the farther is fixated) has the reverse figure ˙. ˙

Scheiner's experiment can easily be illustrated with any convex lens and a pierced screen of suitable size.

107. Range of Accommodation. *a.* Find by trial the nearest point at which a pin seen as in Scheiner's experiment can be seen single. This is the *near point* of accom-

modation. For the short-sighted a *far point* may also be found, beyond which double images reappear.

b. Find how far apart in the line of sight two pins may be, and yet both be seen single at one and the same time. Try with the nearer at 20 cm., at 50 cm., at 2 m. That portion of the line of sight, for points in which the same degree of accommodation is sufficient, is called the *Line of Accommodation.* The length of the line increases rapidly as the distance of the object from the eye increases.

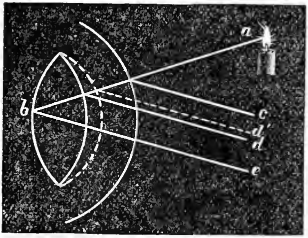
Helmholtz, *A*, 114, 119, Fr. 122 (93), 128 (97).

108. Mechanism of Accommodation. The change in the lens in accommodation is chiefly a bulging forward of its anterior surface. This may be observed as follows: —

a. Let the subject choose a far and a near point of fixation in exactly the same line of vision; close one eye and fix the other upon the far point. Let the observer place himself so that he sees the eye of the subject in profile with about half the pupil showing. Let the subject change his fixation at request, from the far to the near point, and *vice versa*, being careful to avoid any sidewise motion of the eye. The observer will notice, when the eye is accommodated for the near point, that more of the pupil shows and that the farther side of the iris seems narrower. This change is due to the bulging forward of the front of the lens. If the change were due to accidental turning of the eye toward the observer, the farther edge of the iris should appear wider instead of narrower. Notice also that the diameter of the pupil changes with the accommodation.

b. Purkinje's Images. The changes in the curvature of the lens may also be observed by means of the images reflected from its front and back surfaces and from the front of the cornea. Operate in a darkened room. Let the subject choose far and near fixation points as before. Let the

observer bring a candle near the eye of the subject at a level with it and a little to one side, and place his own eye in a position symmetrical to the candle on the other side of the subject's line of sight. Careful examination and some shifting about of the place of the candle and of the observer will show three reflected images of the flame: one on the side of the pupil next the light, easily recognizable, bright and erect, reflected from the surface of the cornea; a second, nearer the centre of the pupil and apparently the farthest back of the three, erect like the first, but very indistinct (more like a light cloud than an image), reflected from the anterior surface of the lens; and a third, a mere point of light, near the side of the pupil farthest from the flame, inverted and reflected from the posterior surface of the lens. When the observer has found these three images, the subject should fixate alternately the near and far points chosen. As he fixates the near point, the middle image will grow smaller, advance, and draw toward the corneal image; when he fixates the far point, the image will enlarge, recede, and move away from the corneal image. The following diagram, after Aubert, illustrates the movement of the middle image; the full lines indicate the positions of the cornea and lens and the course of the rays of light when the eye is accommodated for the far point; the dotted lines indicate the anterior surface of the lens and the direction of the ray reflected from its surface when the eye is accommodated for the near point. Three images similar to those in question can be



observed on a watch glass and a double convex lens held in the relation of the cornea and crystalline.[1]

Helmholtz, *A*, 131–141, especially 131–134, Fr. 142–154 (104–112), especially 142–146 (104–107); Aubert, *A*, 444; Tscherning.

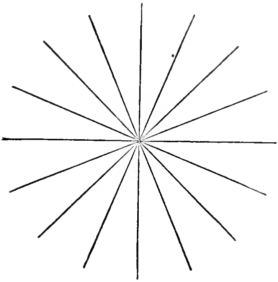
109. Dioptrical Defects of the Eye. Of these defects only two will be considered here: *Astigmatism* and *Chromatic Aberration.* The first is an error in the form or setting of the refracting surfaces, which prevents their bringing parallel light to a focus in a single point. If the curvature of the lens, for example, (or of the cornea), is greater on the vertical meridian than on the horizontal, parallel light falling upon the first will be brought to a focus nearer the lens than that falling upon the second. This makes it impossible for the astigmatic eye to see all parts of a plane figure with equal distinctness at the same time. *Chromatic Aberration* depends upon the different degrees of refraction which different colored lights experience in traversing the lens; those of short wave-length (violet and blue) are most refracted, those of long wave-length (red and orange) least, and the others in order between. The point at which parallel violet rays are brought to a focus is therefore nearer the lens than the point for red. In order, therefore, that the same degree of accommodation may serve to show a red lighted object and a violet lighted object at the same time and both with full distinctness, the red light must be less divergent than the violet; in other words, the red lighted object must be somewhat farther away.

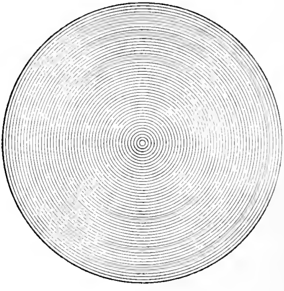
a. Astigmatism. Make a fine pin-hole in a card; hold it at arm's length against a bright background and accommo-

[1] By using a magnifying-glass a second faint corneal image very close to the first can be seen, when the light strikes the cornea well toward one side. When this is counted, as it is by Tscherning, there are four Purkinje images, those from the front and back of the lens becoming the third and fourth in the enumeration, instead of the second and third.

date the eye for a nearer point, or put on convex glasses. The spot will not appear as a little circle of light, as it would if the lens and cornea were perfect in form, but as a more or less irregular star or flower-shaped figure in which portions of several images of the hole may be made out. Accommodate for a point considerably beyond the card and notice the change in the figure.

These irregularities (phenomena of *Irregular Astigmatism*) disappear, however, with exact accommodation, but another kind (*Regular Astigmatism*) is then to be observed. Close one eye and look with the other at the centre of the radiating figure below. Notice which lines appear with greatest blackness and distinctness. Try the effect of increasing and decreasing the distance. Try also the other eye.





Something of the same kind is to be seen in the set of concentric circles; also evidences of irregular astigmatism when accommodation is changed or when the distance of the diagram is increased or decreased. Notice especially the rayed appearance and the distortion of the inner circles when the eye is accommodated for a greater distance than

that of the diagram. On the latter peculiarity, see von Bezold.

b. Chromatic Aberration. Bend a fine platinum wire into a ring half an inch in diameter, and heat it white hot in the flame of a Bunsen burner. Look at the ring through a pin-hole in a black card held at such a distance that the ring lies close to the edge of the field of the pin-hole all around. Accommodate the eye for the centre of the ring, and observe that the outer edge of the ring appears bright red, the inner edge blue or violet. Substitute for the card a bit of blue glass, and accommodate first for the glass, then for a point some distance beyond the ring. In the first case the outer and inner edges of the ring (except as astigmatism interferes) will both be blue; in the second case they will be red. The ordinary blue glass allows both red and blue light to pass through it.

Look at the edge of the window frame next the pane, and bring a card before the eye so that about half the pupil is covered; if the card has been brought up from the frame side, the frame will be bordered with yellow; if from the pane side, with blue. In ordinary vision these fringes do not appear, because the colors partially overlap and produce a practically colorless mixture.

Von Bezold's Experiment. Look at the parallel lines of the left figure in Ex. 118 with imperfect accommodation, e.g., through convex spectacles, and observe the aberration colors. If a set of heavy concentric circles (separated by equal spaces, and beginning with a central black dot of a diameter equal to the width of the lines) is used instead of the straight line figure, it will be possible by changing its distance from the eye to find a position in which the aberration colors so overlap that dark and light seem to have changed places, and the central spot is light instead of dark. The spiral figure with Ex. 128 will show

something of the effect, but the central black spot is too large to show it completely.

Both astigmatic differences and the aberration colors may at times influence judgments of distance.

On *a*, Helmholtz, *A*, 169 ff., Fr. 187 (138) ff. On *b*, Helmholtz *A*, 156–164, Fr. 172–179 (125–131); von Bezold; Tumlirz.

ENTOPTIC APPEARANCES.

110. Floating Particles in the Media of the Eye and on its Surface; *Muscæ Volitantes.* Fix a lens of short focus at some distance from a bright gas or candle flame. Set up in the focus of the lens a card pierced with a very fine hole; bring the eye close to the hole and look toward the light. The eye should be far enough from the hole to prevent the edge of the lens from being seen. The rays of light that now reach the eye are strongly divergent, and the crystalline lens does not bring them to a focus on the retina, but only refracts them to such a degree that they traverse the eye nearly parallel, and thus in suitable condition for casting sharp shadows upon the retina of objects on or in the eye.

a. The lens will appear full of light, and in it will be seen a variety of shadings, blotches, and specks, single or in strings, the outward projection of the shadows just mentioned. The figures in this luminous field will vary from person to person, even from eye to eye, but in almost every eye some will be found that move and some that remain fixed or only move with the eye. Of the moving figures some are due to particles and viscous fluids on the surface of the eye; they seem to move downward, and are changed by winking. Notice, for example, the horizontal bands that follow a slow dropping and raising of the upper lid. Such appearances as these, since their cause is not really in the eye but outside of it, have been called *pseudentoptic* by Laqueur. Others, the *muscæ volitantes,* are frequently

noticed without any apparatus; they appear as bright irregular threads, strings of beads, groups of points, or single minute circles with light centres. They seem to move downward in the field, but actually move upward in the vitreous humor where they are found. Of the permanent figures, some are due to irregularities of structure or small bodies in the crystalline and its capsule (spots with dark or bright centres, bright irregular lines, or dark radiating lines corresponding probably to the radial structure of the lens); others of a relatively permanent character, it is said, can be produced on the cornea by continued rubbing or pressure on the eyeball.

b. The round spot of light in which these things are seen represents the pupil, and the dark ground around it is the shadow of the iris. Notice the change in the size of the spot of light, as the eye is accommodated for different distances (cf. Ex. 108), or as the other eye is exposed to, or covered from, the light. The change begins in about half a second. It shows the close connection of the iris mechanisms of the two eyes, and is typical of the way in which the two eyes co-operate as parts of a single visual organ.

Some of these entoptic observations may be made with a pierced card alone, or simply by looking directly at a broad expanse of clear sky without any apparatus at all.

Helmholtz, *A*, 184–192, and Tafel I., which shows the appearance of several of these entoptic objects, Fr. 204–214 (149–156) and Pl. V., also 548–558 (419–427); Laqueur.

111. Retinal Blood-vessels, Purkinje's Vessel Figures. *a.* Concentrate a strong light (preferably in a dark room), or even direct sunlight, with a double convex lens of short focus on the sclerotic in the outer corner of the eye of the subject, requesting him to turn the eye toward the nose

and giving him a dark background to look toward. Make the spot of light on the sclerotic as small and sharp as possible, and give to the lens a gentle to and fro or circular motion. After a little the subject will see upon the field, which the light makes reddish-yellow, the dark branching figure of the shadows of the retinal vessels. Notice that the spot directly looked at is partially surrounded, but not crossed, by the vessels. In this lies the yellow spot (*macula lutea*), the retinal area of clearest vision. The centre from which the vessels radiate lies in the point of entrance of the optic nerve. In this form of the experiment the light radiates in all directions within the eye from the illuminated point of the sclerotic.

b. Somewhat the same sort of image is to be secured by moving a candle about near the eye, below it and a little to one side. In this experiment some indication of the region of the yellow spot is to be seen. This time the light enters by the pupil, forms an image on a part of the retina somewhat remote from the centre, and this retinal image is itself the source of the light by which the vessel shadows are cast.

c. Look through a pin-hole in a card, held close before the eye, at the sky or some other illuminated surface, or at a broad gas-flame. Give the card a rather rapid circular motion, and the finer retinal vessels in the region of the yellow spot will readily be seen, among them also a small colored or slightly tinted spot (best seen, perhaps, by gas-light) representing the *macula*, and in its centre a shadowy dot (representing the *fovea*, the point of clearest vision), which appears to rotate when the motion of the card is circular. If the card is moved horizontally, the vertical vessels alone appear; if vertically, the horizontal vessels. Notice also the granular appearance of the *macula;* the granulations have been supposed to represent the visual

cones of that region. The finer retinal vessels can also be seen when looking at the vacant field of a compound microscope, if the eye is moved about rapidly.

In all cases it is important that the shadows be kept moving; if they stand still, they are lost. The explanation is partly physiological (the portions of the retina on which the shadows rest soon gain in sensitiveness enough to compensate for the less light received) and partly psychological (moving objects in general arouse spontaneous attention, and those whose images rest continuously on the retina without motion are particularly subject to neglect).

Once having become familiar with these vessel figures, it is often possible for the observer to see traces of them without any apparatus. Parts of them, with something of the yellow spot, may sometimes be seen for an instant as dark figures on the diffusely lighted walls and ceiling, or as light figures on the dark field of the closed eyes, when the eyes are opened and closed after a glance at the window on first waking in the morning, or as blue figures when looking at the snow and winking on a bright winter morning.

Helmholtz, *A*, 192–198, 555, Fr. 214–221 (156–161), 528 (402).

112. Retinal Circulation. Look steadily through two or three thicknesses of blue glass at the clear sky or a bright cloud, and observe the bright points darting hither and thither like bees in a swarm or snowflakes on a windy day. Careful observation will also establish that the bright points are followed by shadowy darker ones. Pick out a speck on the window to steady the eyes, and observe that while the movements of the points seem irregular the same lines are retraced by them from time to time. When several of their courses have been accurately determined for one of the eyes, repeat the experiment for demonstrating the finer retinal vessels (Ex. 111, *c*), and notice that fine vessels

are found which correspond to the courses that the points seem to follow. These flying points can be seen without the glass by a steady gaze at an evenly lighted bright surface, and sometimes a rhythmical acceleration of their movements will be found, corresponding to the pulse. Helmholtz explains the phenomenon by a temporary clogging of fine capillary vessels by large blood corpuscles. The bright lines (the apparent tracks of bright points) are really the relatively empty capillary tubes ahead of the corpuscles, which, after an instant, are driven onward by others crowding behind, which in turn give the shadow that apparently follows the bright points.

Helmholtz, *A*, 198 f., Fr. 221 (837), 555 (425); Rood.

113. The Blind Spot. Mariotte's Experiment. The point of entrance of the optic nerve is unprovided with visual end-organs and is irresponsive to light. This insensitiveness is easily demonstrated with the diagrams below.

a. Close the left eye, and keeping the right fixed on the upper asterisk in the diagram move the latter toward the eye and away from it till a point is found where the black oval disappears. For the blind spot of the left eye, turn the diagram upside down and close the right eye.

The blind spot may be demonstrated simultaneously in both eyes with the figure on the next page. The experimenter should look at the asterisk while he holds a card

in the median plane of his head, to prevent each eye from seeing the other's part of the diagram.

b. To draw the projection of the blind spot, arrange a head-rest opposite a vertical sheet of white paper, and 15 or 18 inches distant from it. Put a dot on the paper for a fixation point. Fasten upon the end of a light rod a bit of black paper about 2 mm. square or blacken the end of the rod with ink. Bring the face into position, close one eye, and fix the other upon the dot. Move the rod slowly so as to bring the little square over the part of the paper corresponding to the blind spot, dotting on the paper the points where the square disappears or reappears. Repeat at various points till the outline of the projection of the blind spot is complete. If the mapping is carefully carried out, the map will probably also show the points of departure of the large blood-vessels that enter with the nerve.

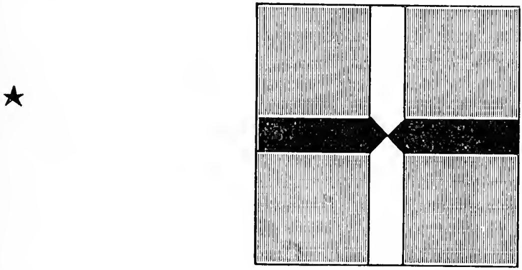
Helmholtz, *A*, 250–254, Fr. 284–289 (210–214).

114. The Filling-out of the Blind Spot is of considerable psychological interest. The mind supplies what is lacking in the sense, and in doing so is influenced both by the sensations of the parts of the retina surrounding the spot and by previous experience. In ordinary two-eyed vision the blind spot of one eye corresponds to a seeing spot in the other, and this with the movements of the eyes amply supplies the defect. The spot, furthermore, lies so far out of the range of clear vision that its existence is habitually overlooked, even in monocular vision.

a. When the image of the oval in *a* of the last experi-

ment is brought wholly upon the spot, the paper seems an unbroken white, because the adjacent parts of the retina are stimulated with white. When, however, the diagram is held a little nearer so that the edge of the black oval can be seen, the filling is part black and part white.

b. The effect of experience appears when the oval is replaced by such a figure as that below, or any other in which the bars stand out well from one another and the background.



When the image of the middle of this diagram falls upon the blind spot, one bar will seem to cross completely over the other. Bars that cross are so much more frequent in experience than those that are mitered together that the sensations of the adjacent parts are thus interpreted. Skill in observation in indirect vision seems to hinder this filling-out process somewhat, probably by aiding in more exact distinguishing of the character of the sensations received. Both Helmholtz and Aubert find themselves unable to determine how the parts of the figure resting on the blind spot are related.

Helmholtz, *A*, Fr. 734–745 (574–583); Aubert, *A*, 595.

115. The Yellow Spot, the *Macula Lutea.* The projection of the yellow spot in the visual field can be made visible in several ways. Two have already been mentioned in Ex. 111; others are as follows: Close the eyes for a few seconds and then look through a flat-sided bottle of chrome alum solution at a brightly lighted surface or at the clear sky. In the blue-green solution a rose-colored spot will be seen which corresponds to the yellow spot. The light that comes through the chrome alum solution is chiefly a mixture of red and green and blue. The pigment of the yellow spot absorbs a portion of the blue and green and transmits the rest, which makes a rose-colored mixture, to the visual organs behind it. The same can be very beautifully demonstrated with violet or purple gelatine sheets.

Helmholtz, *A*, Fr. 548–551 (419–421); Maxwell; Sachs; Hering, *C*.

116. Intermittent Illumination. The region of the yellow spot can be seen, together with many other curious figures and patterns, when the illumination of a single eye is made intermittent by moving the spread fingers rapidly to and fro before it. Something may be seen when the open eyes are fixed on a uniformly lighted surface, but more when they are turned with closed lids toward a bright sky or the sun itself. The figures probably differ in different eyes and some are beautiful and elaborate. Sometimes with steady fixation the figures give place more or less completely to a general streaming of fine particles, suggesting the flying specks of Ex. 112, but finer and of less regular course. Vierordt credited the appearance to the circulation of the blood in the retinal vessels; Helmholtz is inclined to think the fine particles lymph corpuscles rather than blood corpuscles. Similar phenomena are to be observed with black and white disks when rotated at less speed than that required for uniform mixing of the black and white.

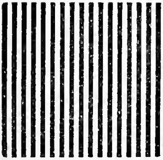
Helmholtz, *A*, 532 f., Fr. 502 (381) f.; Exner, *F*.

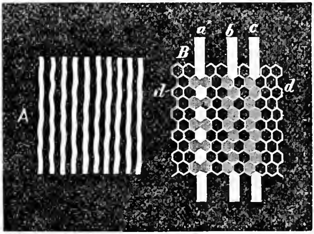
117. Acuteness of Vision, *Minimum Visibile.* *a.* Place the parallel line diagram used in Ex. 118 in a good light and walk backward from it till the lines can just no longer be distinguished as separate. If the experimenter's eyes are not normal, he should use glasses that fit his eyes for distinct vision at the distance required. Measure the distance between the eye and the diagram, and calculate the angle whose apex lies in the crossing point of the lines of direction (about 7.2 mm. back of the cornea and 15.6 mm. in front of the retina) and whose base is the distance from the middle of one line of the diagram to the middle of the next; in this diagram 1.6 mm. This angle measures the least visible extent when discrimination is involved; the least luminous extent that can still impress the retina is far smaller, as witness the visibility of the stars. On the supposition that if the sensations of two cones are to be separable they must be separated by an unstimulated cone, or at least by a less stimulated one, it has generally been considered that the cones could not subtend a greater angle than that found in this experiment, 60″—90″, representing 0.004—0.006 mm. on the retina, and this agrees well with microscopical measurements. But as Helmholtz notices (*Phys. Opt.*, 2d ed., p. 260), this experiment does no more than prove that there are on the retina rows of sensitive elements, the middle lines of which are separated by the angular distance found in the experiment. The elements themselves, if properly arranged, may be somewhat larger. Calculation of the number of such elements in a sq. mm. of the retina, based on this view of the experiment, agrees well in the case of Helmholtz's own determination with the result of microscopical counting.

b. The discriminative power of the retina falls off rapidly in all directions from the *fovea* — more rapidly above and below than in a horizontal direction. Arrange a head-rest

and perpendicular plane as in Ex. 113, *b* (or if a perimeter is at hand use that). Place upon the end of the rod used in that experiment a card on which have been made two black dots 2 mm. in diameter and 4 mm. from centre to centre. Move the card horizontally toward the fixation point, beginning beyond the point at which the two dots can be distinguished and moving inward till they can just be distinguished. Measure the distance from the fixation point, and repeat several times both to the right and left of the fixation point, holding the card so that both dots are in each case equally distant from that point. Try the same for the vertical meridian.

Helmholtz, *A*, 255–264, Fr. 291–301 (215–223); Uhthoff. On *a*, Aubert, *A*, 579–585; on *b*, 585–591. On *b*, see also Exner, *D*, 242 ff.





118. Bergmann's Experiment. Place the left hand diagram in a good light, and look at it from a distance of a yard and a half or two yards. Observe the apparent bending and beading of the lines. This is believed by Helmholtz to be due to the mosaic arrangement of the visual cones. The cones that are touched by the image of one of the white lines are stimulated in proportion as they are more or less touched. Those that are much stimulated furnish the sensation of the white line and its irregularities; those that are little

stimulated join with those that are not touched at all to give the image of the black line and its irregularities. This is schematically represented in the right hand cut. Von Fleischl, on the other hand, has made experiments to show that the bending and beading of the lines is not connected with the retinal mosaic, but rather with movements of the eyes that sweep the point of fixation backward and forward across the lines. Further than this his explanation does not go.

Helmholtz, *A*, 257–258, Fr. 293 294 (217–218); von Fleischl.

119. Mechanical Stimulation of the Retina. *a.* Phosphenes. Turn the open or closed eye as far as possible toward the nose and press on the eyelid at the outer corner with the finger or the tip of a penholder. On the opposite side of the visual field will be seen a more or less complete circle of light surrounded by a narrow dark band, outside of which again is a narrow band of light. Notice the color of the light seen. Get phosphenes by pressure at other points of the eyeball.

b. Press the eye moderately with some large object, say, the angle of the wrist when the hand is bent backward, and continue the pressure for a minute or two. Peculiar palpitating figures will be observed and strange color effects. The former Helmholtz compares to the tingling of a member that is "asleep."

c. Standing before a window, close the eyes and turn them sharply from side to side. As they reach the extreme position in either direction, observe immediately in front of the face a sudden blue spot surrounded by a yellow band. A second fainter spot farther from the centre in the direction of motion may also be seen. The appearance of the first spot is due to a mechanical stimulation of a portion of the retina at the edge of the blind spot in the eye that turns

inward. The second spot belongs to the corresponding area in the other eye.

Helmholtz, *A*, 235–239, Fr. 266–270 (196–200), 744 (583) f.

The own light of the Retina.

120. Idio-retinal Light, Light Chaos, Light Dust. *a.* Close and cover the eyes so as to exclude all light, taking care not to press them, or experiment in a perfectly dark room. Let the after-effects of objective light fade away, and then watch the shifting clouds of retinal light. The cause of the retinal light is not altogether clear, but it is supposed to be a chemical action of the blood on the nervous portion of the visual apparatus. Aubert estimates its brightness at about half the brightness of a sheet of paper illuminated by the planet Venus when at its brightest.

b. When awake in the night time in a room that is almost perfectly dark (e.g., in which the form of the window and the large pieces of furniture cannot be made out), notice that the white clothing of the arms can be seen faintly when they are moved about, but not when they are still. In the last case the very faint light they reflect is not sufficient to make them distinguishable from clouds of idio-retinal light.

Helmholtz, *A*, 242–243, Fr. 274–275 (202–203). On *b*, Helmholtz, *B*.

121. Electrical Stimulation of the Visual Apparatus. Moisten thoroughly with salt water both the electrodes and the portions of the skin to which they are to be applied. Place one of the electrodes on the forehead (or on the edge of the table and lay the forehead upon it), the other on the back of the neck; or, if the current is strong enough, hold it in the hand or lay it on the table with the hand upon it. At each opening or closing of the circuit, a bright flash will be seen, whether the eyes are closed or open. With the eyes closed and covered, the effects of the continuous current

may be observed. In this case it is well to apply the electrode slowly and carefully so as to avoid as much as possible the flash caused by the sudden closing of the circuit. When the positive electrode is on the forehead, the negative on the back of the neck, a transient pale violet light will be seen distributed generally over the field and forming a small bright spot at its centre. Sometimes traces of the blind spot also appear. The violet light soon fades, and on opening the circuit there is a notable darkening of the field, with a momentary view of the blind spots as bright disks. When the negative electrode is on the forehead, the positive on the back of the neck, the phenomena are in general reversed, the darkening occurring on closing the circuit, the violet light on opening it. Helmholtz sums up these and other experiments in the following law: "Constant electrical circulation through the retina from the cones toward the ganglion cells gives the sensation of darkness; circulation in the contrary direction gives the sensation of brightness." (*Phys. Opt.*, 2d ed., p. 247.) That the blind spot should appear as a disk of different color from the rest of the field seems to be due to the fact that the sensitive parts of the retina immediately surrounding it are somewhat shielded from the electric current, and as usual their condition is attributed to the blind spot also. The experiment is not altogether a pleasant one, on account of the feeling which the current produces in the head, the "electrical taste" in the mouth, and the reddening of the skin under the electrodes.

Helmholtz, *A*, 243–248, Fr. 275–281 (203–207), 744 (583).

Retinal Fatigue and Adaptation.

122. Retinal Fatigue. Stare with perfectly fixed and motionless eyes at a selected spot on a variegated carpet or wall paper, and notice the levelling effect of fatigue. The

differences in color and pattern gradually disappear, and the whole field becomes a nearly uniform cloud. The parts of the retina that are strongly stimulated are brought down to the general level; those that are little stimulated are built up to it. Every wink or slight movement of the eyes causes a general brightening up of the field and restoration of vision. The experiment is particularly easy to make when looking at a uniform surface with faint shadows lying on it.

Helmholtz, *A*, 508, 555 ff., Fr. 478 (362), 527 (402) ff.; Fick, *B*, 222; Treitel; Hering, *C*. See also the discussion on this topic by A. E. Fick and Hering.

123. Adaptation of the Eye. *a.* The adjustment of the eye to the intensity of its illumination is effected partly by change in the size of the pupil, and partly by changes in the retina itself. The first is of common observation, and the connection of the two eyes in this respect has been noticed in Ex. 110, *b*. The effects of going from a dark room into a light room and *vice versa*, and the gradual improvement of vision on remaining in one or the other, are also familiar.

b. It has not, however, been so generally observed that adaptation to very weak lights is much more favorable to the perception of colorless light than to colored. This may easily be observed in a dark room with single flashes of a rather faint Geissler tube. Before the room is darkened, and for a short time after, the colors of the light are readily perceived. After some time, however, they nearly or quite fail, seeming to be lost in the increased brilliancy of the white light. It is important that there should be an interval between the flashes sufficient to allow all the effects of one to disappear before another is given. If the room is not completely dark, the head of the observer and the tube

must be covered closely with an opaque cloth to allow full adaptation.

Aubert, *A*, 483 f., *B*, 25 ff.; Charpentier, *A*, 154 ff.; Treitel; Hering, *C*. On *b*, Hillebrand.

AFTER-IMAGES.

After-images, Accidental or Consecutive Images. After-images in which the relations of light and shade of the original object are preserved are called *Positive After-images.* Those in which these relations are reversed (as in a photographic negative) are called *Negative After-images.* Positive after-images are of various colors, but most important to notice here are those of the color of the object (*like-colored*), and of the complementary color (*opposite-colored*). Negative after-images, so far as observed, are always *opposite-colored.* All after-images, especially the positive, can best be observed in the morning when the eyes are well rested.

124. Negative After-images. *a.* Look steadily for a minute at a fixed point of the window, then at a white screen or an evenly lighted, unfigured wall; the dark parts of the window will now appear light and the light dark.

b. Get a lasting after-image and look at a corner of the room, or at a chair or other object of uneven surface; notice how the image seems to fit itself to the surface upon which it rests. After a little practice it is also possible at will to see the image floating in the air instead of lying on the background.

c. Look steadily at a bright-colored object or some bits of colored paper, then at the screen; observe that the colors of the after-images are approximately complementary to the colors of the objects producing them.

d. Negative After-images upon a Background faintly Tinged with the Stimulating Color. Fasten upon the color-mixer a

white disk upon which has been painted a six rayed star of red. Set the disk in rapid rotation, bring the eyes within eight or ten inches of the disk, and after half a minute suddenly withdraw them to thirty or forty inches. As the head is drawn back the complementary color will be seen to press in upon the disk from all sides while the red contracts. When the head is again approached to the disk the red will enlarge and the blue-green disappear. The cause of the rushing in of the blue in the first case is the contraction of the retinal image, which of course decreases in size as the head is drawn back, and is thus brought upon parts of the retina that have been more strongly stimulated. When the head approaches the disk the retinal image enlarges and its outer portion lies on a fresh area.[1]

Negative after-images are sometimes very lasting, and for that reason are those most frequently noticed in ordinary experience. They are phenomena of retinal fatigue (Helmholtz), or of retinal restitution (Hering).

125. Positive After-images. These images are not difficult to see, if after a brief stimulation the eye is shielded from further action of light. Thus, when the gas is suddenly turned off in a dark room, the positive image of the flame and the burner is very easily seen.

a. Look for an instant (one-third of a second) at the window, then close and cover the eyes. Notice that the after-image is like the window in distribution of light and shade, bright panes and dark bars, and at first like it also in color. After some practice it is also possible to see, for a small fraction of a second, the positive after-image of almost any bright object on suddenly turning the eyes from the object to some other part of the field, especially if the latter is dark. The positive after-image is of short duration and less readily observed than the negative. It has generally

[1] For a still simpler experiment, see *Mind*, Ser. 2, II., 1893, 485, note.

been considered a phenomenon of retinal inertia, a prolongation of the original retinal excitation, and such a prolongation does undoubtedly exist. Charpentier and Hess, however, in experiments with very brief stimulation, have found a transient negative image coming between the original impression and the ordinary positive after-image observed with longer stimulation. The full series would then be: 1. Prolongation of the original stimulus; 2. First Negative Image; 3. Ordinary Positive After-image; 4. Ordinary Negative After-image.

b. Colored Positive After-images. Look for an instant at a gas flame through a piece of red glass, then close and cover the eyes and observe the red image; repeat the experiment, continuing the fixation of the flame for half a minute; the resulting after-image will be bright as before but of the opposite color.

c. After-images on Dark and Light Backgrounds. Get an after-image of the window of not too great intensity, and project it alternately on a sheet of white paper and the dark field of the closed and covered eyes; it will be found negative on the white background and positive on the dark. Some observers find a periodic reappearance of positive after-images, or an alternation of positive and negative images, without a change of background.

d. Sequence of Colors. Get a good after-image of the window, and observe with closed and covered eyes the play of colors as the image fades. Try several times and observe that the order of succession is the same. According to Hering, this play of colors would not take place if the original stimulus were absolutely colorless.

On Exs. 124 and 125, consult the following: Helmholtz, *A*, 480 ff., 501 ff., Fr. 446 (338), 471–500 (357–380); Wundt, *A*, 3te Aufl., I., 472–476, 4te Aufl., I., 512 ff.; Hess; Charpentier, *B*. See also references given in Chap. VI. for Successive Contrast.

126. Effect of Eye-motions on After-images. Get a moderately strong after-image of the window; look at the wall and keep the eyes actively in motion. The image will be seen with difficulty while the eye is in motion; when, however, the eye is brought to rest, it will soon appear. In general, any visual stimulus that moves with the eye is less effective than one that does not.

Exner, *A.*

127. The Seat of the After-image. An after-image due to stimulation of one eye may, under proper conditions, sometimes seem to be seen with the other. From this it has been inferred that the seat of after-images is central, not peripheral; that is, in the visual centres of the brain, higher or lower, not in the retina. The following experiments show, however, that the after-image is really seen with the eye first stimulated, and so render the hypothesis of a central location unnecessary.

a. Look steadily for a considerable time at a bit of red paper on a white ground, using only one eye, say the right, and keeping the other closed; when a strong after-image has been secured, remove the paper, close the right eye, open the left, and again look steadily at a fixed point on the white ground; after a little the field will darken and the after-image will reappear. If the red does not produce a sufficiently lasting image, substitute for it a gas flame or some other bright object.

b. That we have really to do with the eye originally stimulated (its present dark field suppressing the light one of the other eye), appears from such experiments as the following: Get the after-image as before; then open both eyes and bring a bit of cardboard before the eyes alternately. Bringing it before the left eye rather brightens the image; bringing it before the right dims or abolishes it.

The image is thus chiefly affected by what affects the right eye.

c. Get the after-image again, and close and cover both eyes; observe the color of the after-image, as projected on the dark field; then open the left eye, letting the right eye remain closed and covered. The after-image will be seen, not in the color it has when the right eye is open and the image is projected in the light field, but in that which it has in the dark field of the closed eye.

These experiments prove that after-images belong to the stimulated half of the visual apparatus, but they do not show whether the images belong to the retina of that half or to the nervous centres connected with it. Other considerations, such, for example, as the fact that the image follows every motion of the eye, even those that are usually unconscious, is affected by pressures exerted on the eyeball and by electric currents sent through it, together with Exner's direct experiments on retinal and optic nerve stimulation, support the retinal location, in favor of which current opinion is practically unanimous. Some observers, however, have been able to get a binocular after-image of a somewhat different character; see binocular section of Chap. VI.

Delabarre; Exner, *D*, 246 ff. and *E*; Fick and Gürber, 296 ff.

128. After-images of Motion. These after-images can be secured from almost any continuously moving object. They are often unpleasantly striking after looking at the water from the deck of a vessel or at the landscape from a car window. In the experiments below, variations of one of the laboratory methods of producing them are given.

a. Fasten upon the rotation apparatus a disk bearing a large number of equal black and white sectors; set it in slow rotation and gaze fixedly at it. The rate must not

be fast enough to blur the outlines of the sectors very much. After a moment or two of steady fixation, bring it suddenly to rest and observe its slow illusory backward movement.

b. Fasten on the apparatus a disk like that in the accompanying cut, and get an after-image as before, fixating the centre. Bring the disk suddenly to rest, or look away from it to a page of print or into the face of a bystander and notice the apparent shrinking or swelling, reversing the previous motion of the spiral. Illusions of increase or decrease of distance sometimes accompany those of motion with this disk. Repeat the experiment, but this time instead of looking at some object, close the eyes and turn them toward the sky or other source of bright light. The apparent motion will be observed again in the red-yellow field.

c. Hold over half of the disk while in rotation a piece of cardboard, fixate the centre of the disk, and get the after-image. Observe that the after-image is limited to the portion of the retina stimulated.

d. Get a monocular after-image of the spiral, with the right eye, for example. Then close the right eye and open the left; the after-image of motion will be projected like that of color in Ex. 127.

e. Hold just above the spiral disk a larger disk of pasteboard, cut with a radial slot an inch or two wide. When the spiral is now revolved a narrow strip will be seen in

which the motion is in one direction only. Get a strong after-image and observe it with closed eyes as in *b* above. It will sometimes be possible, at least for a short time, to get a reversal of the previous illusion; the part of the image corresponding to the slot will appear to stand still while the adjacent parts move, or both will appear in motion in opposite directions. This experiment is apparently easier to get with the antirrheoscope, where the moving field is larger. With that instrument the effect mentioned can be seen in the ordinary projected after-image.

When a strong after-image is projected upon a set of straight lines at right angles to the direction of movement, some observers have seen the lines more or less distorted by it (Budde saw them thus affected when the lines did not cross, but only entered the moving part of the field); others have found the lines entirely unaffected. It seems probable that the breadth and distinctness of the lines have something to do with this difference of results.

Exner, who believes in the retinal seat of color after-images, is inclined to give a more central location to these of motion. In his opinion such experiments as those above indicate also that our knowledge of such motions is a *sensation*, not a *perception*.

After-images of motion have been explained by actual, though unconscious, movements of the eyes, like the apparent movements of objects in dizziness. This is certainly incorrect; for in *b* it would seem necessary that the eyes should move in all directions at once, and *c* shows that the effect is limited to a portion of the field, which would be impossible if it were due to actual eye motions. The same was demonstrated by Dvorák by means of a disk with three concentric spirals, the inner and outer ones being drawn in the same way, (right-handed spirals, for example), while that between was drawn in the reverse direction. How far

some psychical representation of ocular motions co-operates in the illusion would be hard to say.

Helmholtz, *A*, Fr. 766–769 (603–605); Bowditch and Hall; Mach, *A*, 59–61 (see also 61–65 for yet another kind of after-image), and *B*, 65–67; Exner, *B* and *C*, 440 ff.; Dvorák; Budde; von Fleischl; Heuse; Zehfuss.

Movements of the Eyes.

The eye is a moving as well as a seeing member; and its motor functions are of great importance for psychology, especially for the theory of the visual perception of space. The experiences of the eye in motion have a controlling influence upon its perceptions even when at rest, as will appear in some of the experiments of Chap. VII.

All motions of the eye may be conceived as rotations of greater or less extent about one or more of three axes: a *sagittal axis*, corresponding nearly with the line of sight; a *frontal axis*, extending horizontally from right to left; and a *vertical axis.* Theoretically all these intersect at right angles in the *Centre of Rotation* of the eye. As a landmark from which to measure eye-movements, that position (approximately) is taken which the eyes assume when the head and body are erect and the eyes are directed forward to a distant horizon. This is known as the *Primary Position* of the eyes (or the lines of sight); any other is a *Secondary Position.* The point on which the eyes are fixed when in the primary position is the *Primary Fixation Point*, or *Principal Point of Regard.* The *Field of Vision* is the extent of space that can be seen with the eye at rest. The *Field of Regard* is the extent of space that can be seen when the eyes are moved. In the following experiments the word *Rotation*, except in the expression "centre of rotation," is reserved for turnings about the sagittal axis.

129. Reflex Movements of the Eye. Of the first importance among eye movements is the constant reflex tendency of the eye to move in such a way as to bring any bright image lying on a peripheral part of the retina, or any to which attention is directed, into the area of clearest vision. Many evidences of this tendency will be found in the ordinary course of vision. By way of experiment, try to study attentively a *musca volitans* or a negative after-image that is just to one side of the direct line of sight. The apparent motion of the object measures the energy of the reflex.

130. Associated Movements of the Eyes. The two eyes form a single visual instrument; and even when one eye is closed, it follows to a considerable degree the movements of its open companion. Movements upward or downward in normal vision are always performed simultaneously by the two eyes.

a. Close one eye, and, resting the finger-tip lightly on the lid, feel the motions of that eye as the other looks from point to point of the field of regard.

b. Get a monocular after-image, as in Ex. 127, and when it seems visible to the open eye, notice that it accompanies the fixation point of that eye as it moves from point to point of the field of regard.

Aubert, *A*, 651 ff.; Hering, *A*, 519 ff.

131. Motions of the Eyes when the Lines of Sight are Parallel. The movements here considered are somewhat simplified for easier exposition.

a. Donders's Law; the Law of Constant Orientation (Helmholtz); the Law of Like Position with Like Direction (Hering). It is evident that when the eye is fixed upon some point of its field, e.g., ten degrees upward and fifteen degrees to the right of the primary position, it is not thereby fixed

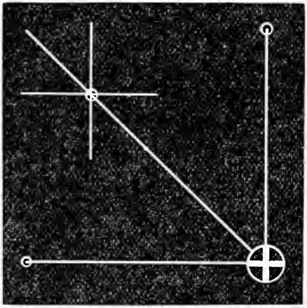
as regards its sagittal axis, but might conceivably assume an indefinite number of positions by different degrees of rotation about that axis. It might also, if not entirely free in its rotation, rotate now through one angle and now through another, depending on the direction in which the line of sight had moved to reach the position in which it is then found. As a matter of fact, however, it does not assume an indefinite number of positions, but one and only one, no matter by what movements the line of sight has come to that point. This is Donders's Law; and the fact that it expresses is of importance for sure and easy recognition of directions in the field of regard, and for deciding whether or not objects in the field have moved when the eye itself has been moved. The correctness of this law is easy to demonstrate.

Cut in a sheet of black cardboard two slits an eighth of an inch wide and four or five inches long, crossing at right angles. Set the cardboard in the window or before some other brightly lighted surface. Arrange a head-rest at a considerable distance, and when the head is in position, get a strong after-image of the cross, fixating its middle point. Then, without moving the head, turn the eyes to different parts of the walls and ceiling. The image will suffer various distortions from the different surfaces upon which it is projected, but each time the eye returns to the same point the image will lie as before. If the wall does not offer figures by which this can be determined, have an assistant mark the position of the image upon it. The after-image is of course fixed on the retina and can move only as the eye moves.

b. Listing's Law. This law goes beyond Donders's Law, and asserts that the position is not only fixed, but that in movements from the primary position there is no rotation at all about the sagittal axis. In other words, the final posi-

tion is such as the eye would assume if it were moved from its primary position to the position in question by turning about a fixed axis standing perpendicular at the centre of rotation to both the primary and the new position of the line of sight. To show this requires a little more care than the last experiment.

The observer must be placed at a distance of twenty-five or thirty feet from an extensive wall space, with a suitable head-rest as before. The lines of sight are, of course, not strictly parallel at this distance, but the difference may be neglected. On the wall stretch dark-colored strings as indicated in the accompanying diagram. The cross at the lower right hand corner should be approximately in the primary position for the observer. The longer vertical and horizontal strings should be twelve or fifteen feet long, the inclined one eighteen or twenty feet. The angle that the last makes with the others is not important so long as it is not too small with either. Fixation points of black cardboard or some other conspicuous substance should be affixed as indicated by the little circles. The cross in the corner may be made by pasting strips of bright-colored paper half an inch wide and a foot long on a disk of white cardboard, or (better still) it may be made by the line of junction of four colored sectors, two red and two blue, for example. The disk in either case must be so arranged that it can be turned about its centre and one of its diameters



be made to coincide with the oblique string. When all has been arranged make the following tests: —

Exact determination of the primary position. For most observers this is somewhat depressed below the horizontal position. Let the observer fixate the centre of the disk till he has secured a strong and clear-cut after-image of it and then turn his eyes, taking care not to move his head, to the fixation marks on the horizontal and vertical strings. If the corresponding lines of the after-image coincide with the strings, the head is in the required position. If not, the head must be moved a little to right or left if the error is with the vertical bar, and up or down if with the horizontal. The primary position differs a little from observer to observer, and even with the same observer at different times.

Having found the primary position, have an assistant turn the cross disk so that one of its diameters coincides with the oblique string. Get a clear after-image of it, and look at the fixation point on that string. Again the bar of the cross will lie exactly upon the string, thus showing that no rotation of the eye about the line of sight has taken place. The same would be true for any other direction of motion from the primary position, provided the movement were not of extreme extent. There is then a set of lines, radiating from the primary fixation point, along which the eye can move, so as to bring all parts of the same line successively on the same part of the retina. Direct examination of such a line and comparison of its parts is easy.

Restore the cross disk to its first position, incline the head forward or backward, or turn it to right or left before getting the after-image (thus bringing the eye into a secondary position), and repeat the experiments just made. Notice that the bars do not now coincide with the strings, showing that the eyes have suffered a certain amount of

rotation. Such a rotation appears for all secondary positions (except when the fixation point both at starting and ending lies in a straight line passing through the primary fixation point), but the extent of it is small in the ordinary movements of the eyes, and extreme movements are usually avoided by simultaneous movements of the head.

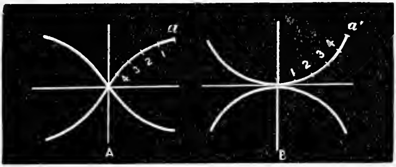
With the cross on the disk vertical as in the cut, get an after-image and fixate the mark on the oblique string. Instead of being rectangular as before, the after-image cross now appears somewhat distorted, like an oblique X. The after-image on the retina of course remains rectangular. The distortion of the image on the wall is the result of the interpretation now placed upon it by the mind. The short string cross at the same centre is known to be rectangular, and if the after-image cross fails to agree with it, the only harmonization of the two is that the latter is not really rectangular. Oblique crosses in such a position in previous experience have given rise to rectangular retinal images so often that this interpretation is immediate, and seems wholly a matter of sensation.

For a fuller account of Listing's Law see Appendix I.

Cf. Helmholtz, *A*, Fr. 601–609 (462–469), 621 (479) ff., 702 (548) ff.; Aubert, *A*, 653 ff.; Wundt, *A*, 3te. Aufl., II., 94 ff.; Hering, *B*, 248 ff.; Le Conte, 164–177.

132. Actual Movements of the Eyes. Wundt-Lamansky Law. Rapid motions of the eyes when they move freely and do not follow strongly marked lines in the field of regard, are not executed exactly according to Listing's Law, though that gives correctly the end positions reached. The axis about which the eye turns is not always constant, and the paths of the fixation point as it moves in the field of regard are therefore not all straight. This is easy to observe as follows. In a dark room turn down the gas till it burns in a very small flame. Then using this as a distant point

of departure in the primary position, look suddenly from it to other points of fixation in various directions about it, and notice the shape of the long positive after-images that result from the motion of the image of the flame over the retina. These will probably have the shape of the radii in the left hand figure below, the vertical and horizontal being nearly straight, and the oblique curved. These, however, do not show immediately the track of the fixation point. The newest part of the after-image is that next the light, the oldest part is that next the fixation point — at *a* in the diagram. If the points of the after-image curve are now interpreted in the order of time (taking the oblique curve to



the right and upward, for example), it appears that the eye at first moved rather rapidly toward the right, but rather slowly upward, while at last it moved rather slowly toward the right and rapidly upward. Plotting a curve in accordance with this interpretation, we get that given in *B*, which shows the true track of the fixation point. By similar plotting the other tracks may be found.

It is said that for some eyes the after-images, though curved, do not coincide with those figured in *A*.

Wundt, *B*, 139 ff., 201–202; Hering, *A*, 450–451; Lamansky.

133. Convergent Movements of the Eyes. The laws of Ex. 131 do not hold for convergent motions of the eyes.

When the lines of sight converge in the primary position, both eyes rotate outward; as the lines of sight are elevated, the convergence remaining the same, the outward rotation increases; as they are depressed, the rotation diminishes and finally becomes zero. On a sheet of cardboard draw a series of equidistant parallel vertical lines one or two inches apart and eight or ten inches long, drawing the left half of the group in black ink, the right half in red. Cross both sets midway from top to bottom by a horizontal line, red in the red set, and black in the black set. Fasten the cardboard flat upon a vertical support, and arrange the head rest in front of it. The horizontal line of the diagram should be on a level with the eyes.

a. If the operator is unable to control the degree of convergence voluntarily, he should fasten a bit of wire vertically between his eyes and the diagram in such a way that it can be moved to and from the eyes. If he is able to control the convergence voluntarily, the wire is unnecessary. Bring the head into position and converge the eyes, giving attention to the diagram. It will be seen that the red and black lines are not quite parallel (or do not quite coincide), and that they are less nearly so as the convergence is increased. The red lines (seen by the left eye) seem to incline a little toward the right, and the black lines (seen by the right eye) toward the left. When the convergence is great, the horizontal lines also will show the rotation. This apparent rotation of the lines is not, as in the case of the after-image, a sign that the corresponding eye has rotated in the same way, but that it has rotated in the opposite way.

b. Repeat this with the head much inclined forward (the equivalent of elevating the eyes) and with it thrown far back (equivalent of depressing the eyes), taking care that the same degree of convergence is maintained. In the first case the apparent rotation of the lines is increased, and

in the second decreased to zero, or even transformed into rotation in the opposite direction.

Helmholtz, *A*, Fr. 609–610 (469–470); Le Conte, 177–191; Hering, *A*, 496 ff.; Aubert, *A*, 658 ff.

134. Involuntary Movements of the Eyes. Lay a small scrap of red paper on a large piece of blue. Fixate some point on the edge of the red. After a few seconds of steady fixation, the color near the line of separation will be seen to brighten, now in the red and now in the blue, thus betraying the small unintentional movements of the eyes.

Helmholtz, *A*, 539, Fr. 511 (389).

BIBLIOGRAPHY.

AUBERT: *A.* Grundzüge der physiologischen Optik, Leipzig, 1876. This work, though obtainable separately, forms a part of the second volume of v. Graefe and Saemisch's Handbuch der gesammten Augenheilkunde. It contains in its three hundred pages a very large amount of matter stated with great brevity and clearness, and is in every way excellent.

B. Physiologie der Netzhaut, Breslau, 1865.

VON BEZOLD: Ueber Zerstreuungsbilder auf der Netzhaut, *v. Graefe's Archiv*, XIV., 1868, ii., 1–29.

BOWDITCH AND HALL: Optical Illusions of Motion, *Journal of Physiology*, III., 1881–82, 297–307.

BUDDE: Ueber metakinetische Scheinbewegungen und über die Wahrnehmung der Bewegung, *Du Bois-Reymond's Archiv*, 1884, 127–152.

CHARPENTIER: *A.* La lumière et les couleurs, Paris, 1888.

B. Réaction oscillatoire de la rétine sous l'influence des excitations lumineuses, *Archives de Physiologie*, Sér. 5, IV., 1892, 541–553, 629–639. Essential points of the same, *Comptes rendus*, CXIII., 1891, 147–150, 217–219. See also *Nature*, XLVIII., 1893, 380.

DELABARRE: On the Seat of Optical After-images, *American Journal of Psychology*, II., 1888–89, 326–328.

DVOŘÁK: Versuche über die Nachbilder von Reizveränderungen, *Sitz.-ber. d. k. Akademie d. Wiss. i. Wien, math.-nat. Classe*, LXI., 1870, *Abth.*, ii. 257–262.

EXNER: *A.* Das Verschwinden der Nachbilder bei Augenbewegungen, *Zeitschrift für Psychologie*, I., 1890, 47–51.

B. Einige Beobachtungen über Bewegungsnachbilder, *Centralblatt für Physiologie*, I., 1887, No. 6, 135–140.

C. Ueber optische Bewegungsempfindungen, *Biologisches Centralblatt*, VIII., 1888, No. 14, 437–448.

D. Ueber die Functionsweise der Netzhautperipherie und den Sitz der Nachbilder, *v. Graefe's Archiv*, XXXII., 1886, i., 233–252.

E. Ueber den Sitz der Nachbilder im Centralnervensystem, *Rep. der Physik*, XX., Protokoll d. chem. phys. Ges. in Wien, 18 März, 1884.

F. Ueber einige neue subjective Gesichtserscheinungen, *Pflüger's Archiv*, I., 1868, 375–394.

FICK, A.: *A.* Dioptrik und Nebenapparate des Auges, Hermann's Handbuch der Physiologie, III., i. 3–138.

B. Die Lehre von der Lichtempfindung. *ibid.*, 139–234.

FICK, A. E., AND GÜRBER: Ueber Erholung der Netzhaut, *v. Graefe's Archiv*, XXXVI., 1890, ii., 245–301. See also Hering's critique, Fick's reply, Hering's rejoinder, and Fick's second reply. *ibid.*, XXXVII. and XXXVIII.

VON FLEISCHL: Physiologisch-optische Notizen (2te Mittheilung), *Sitz.-ber. d. k. Akademie d. Wiss. i. Wien, math.-nat. Classe*, LXXXVI., 1882, *Abth.* iii., 8–25.

HELMHOLTZ: *A.* Handbuch der physiologischen Optik, 2te. Aufl., Hamburg und Leipzig, 1886–1892.

Of this second edition of Helmholtz's work but seven parts have so far appeared. The latest complete edition is the French translation by Javal and Klein (Optique physiologique, Paris, 1867). The references following the experiments are given when possible for both the second German edition and the translation. The figures in parentheses following those for the translation are the pages of the first German edition taken from the double paging of the French version. Having been taken thus at second hand, they may sometimes be in error by a page or

two, but it seemed better to run that risk than to omit them altogether. It is hardly necessary to add that this work is above all others the masterpiece of physiological and psychological optics.

B. Die Störung der Wahrnehmung kleinster Helligkeitsunterschiede durch das Eigenlicht der Netzhaut, *Zeitschrift für Psychologie*, I., 1890, 5–17.

Hering: *A.* Der Raumsinn und die Bewegungen des Auges, Hermann's Handbuch der Physiologie, III., Th. i., 343–601.

B. Beiträge zur Physiologie, Leipzig, 1861–64.

C. Ueber den Einfluss der Macula lutea auf spectrale Farbengleichungen, *Pflüger's Archiv*, LIV., 1893, 277–318.

Hess: Untersuchungen über die nach kurzdauernder Reizung des Sehorgans auftretenden Nachbilder, *Pflüger's Archiv*, XLIX., 1891, 190–208.

Heuse: Zwei kleinere Mittheilungen aus dem Gebiete der physiologischen Optik, *v. Graefe's Archiv*, XXXIV., 1888, ii., 127–134.

Hillebrand: Ueber die specifische Helligkeit der Farben (mit Vorbemerkungen von E. Hering). *Sitz.-ber. d. k. Akademie d. Wiss. i. Wien, math.-nat. Classe*, XCVIII., 1889, Abth. iii., 70–120.

Lamansky: Bestimmung der Winkelgeschwindigkeit der Blickbewegung, respective Augenbewegung, *Pflüger's Archiv*, II., 1869, 418–422.

Laqueur: Ueber pseudentoptische Gesichtswahrnehmungen, *v. Graefe's Archiv*, XXXVI., 1890, i., 62–82. Contains historical references.

Le Conte: Sight, New York, 1881.

Mach: *A.* and *B.*, works cited with same letters in bibliography of Chap. II.

Maxwell: On Color-vision at Different Points of the Retina, *Report of the British Association*, 1870; or Maxwell's Scientific Papers, Cambridge, 1890, Vol. II., 230.

Rood: On a probable means of rendering visible the Circulation in the Eye, *American Journal of Science*, 2d Ser., XXX., 1860, 264. Additional observations on the Circulation in the Eye, *ibid.*, 385.

SACHS: Ueber die specifische Lichtabsorption des gelben Fleckes der Netzhaut, *Pflüger's Archiv*, L., 1891, 574–586.

SCHWARZ: Ueber die Wirkung des constanten Stroms auf das normale Auge, *Archiv für Psychiatrie*, XXI., 1890, 588–617.

TREITEL: Ueber das Verhalten der normalen Adaptation, *v. Graefe's Archiv*, XXXIII., 1887, ii., 73–112.

TSCHERNING: Beiträge zur Dioptrik des Auges, *Zeitschrift für Psychologie*, III., 1892, 429–492.

TUMLIRZ: Ueber ein einfaches Verfahren, die Farbenzerstreuung des Auges direkt zu sehen, *Pflüger's Archiv*, XL., 1887, 394.

UHTHOFF: Ueber die kleinsten wahrnehmbaren Gesichtswinkel in den verschiedenen Teilen des Spektrums, *Zeitschrift für Psychologie*, I., 1890, 155–160. Contains bibliographical notices on *minimum visibile*.

WOLF: Ueber die Farbenzerstreuung im Auge, *Wiedemann's Annalen*, XXXIII., 1888, 548–554.

WUNDT: *A*. Work cited in bibliography of Chapter I.
B. Beiträge zur Theorie der Sinneswahrnehmung, Leipzig, 1862.

ZEHFUSS: Ueber Bewegungsnachbilder, *Wiedemann's Annalen*, IX., 1880, 672–676.

The works of Helmholtz and Aubert mentioned above contain full bibliographies for the earlier literature of all the subjects considered in this and the next two chapters.

CHAPTER VI.

Sensations of Light and Color.

THE aim of the following experiments is not to settle conflicting color theories, but rather to present the most important experimental facts which all color theories must take into account.[1] Authoritative statements of theories may be found as follows: Young-Helmholtz theory; Helmholtz, *A*, 344–350, Fr. 380–387, 424–425, 484 (290–294, 320–321, 367); *B*, 249–256. Hering's theory; Hering, *A*, 70–141; *M*, 76–79. Hering has not yet made a general statement of his theory in its later developments, and his present views must be gathered in more or less fragmentary condition from his numerous special articles. The theories of Helmholtz and Hering are the most prominent of current theories; and something on them, especially on the first, will be found in the physiologies generally, and in some works on color in the arts. Of other theories there are a considerable number; see, for some of them, von Kries; Wundt, *A*, and *B*; Donders, *A* and *B*; Christine Ladd Franklin, *A* and *B*; Ebbinghaus, *A*.

Most color theories attempt to simplify the multiplicity of ordinary color sensations by considering them as compounds of a small number of simple or primary sensations. The number of primary colors is different in different theories; red, green, and violet (or blue) are selected by

---

[1] For concise statements of these facts, see Wundt, *A*, 3te Aufl., I., 487, 501, 4te Aufl., I., 529; and Christine Ladd Franklin, *A*.

the supporters of the Young-Helmholtz theory; red, green, yellow, and blue by Hering, Mach, and others; while Wundt is indisposed to make any particular colors more original for sensation than the rest. The selection has generally been dictated by considerations of physics, or the results of introspective analysis of the sensations; but efforts have lately been made to settle the question by careful examination of the color-blind, and by calculations based upon careful experiments. On the first, see the literature on color-blindness below; on the second, see Helmholtz, *A*, 456 ff., *D*, and König und Dieterici, *A*. White is unquestionably a sensation, and Helmholtz and Hering agree in holding the same with reference to black; though Fick and some others disagree, regarding it rather as the absence of sensation.

A given color sensation may be changed in three ways: in *color-tone*, in *saturation*, and in *intensity*, or, to use Maxwell's terms, in *hue*, *tint*, and *shade*. Changes in *color-tone* are such as are experienced when the eye runs through the successive colors of the spectrum. Changes in *saturation* are such as are produced by the addition or subtraction of white; when much white light is added, the color is a little saturated. Changes in *intensity* are changes in the brightness of the color. Changes in saturation and in intensity, if excessive, involve some change of color-tone also. Hering's theory does not admit changes in the *intensity* of light and color sensations in any ordinary sense of the word. Colors that by others are said to be of low intensity are regarded by Hering and his school as mixed with a large proportion of black; similarly those of high intensity are mixed with much white. In Hering's theory the possible changes are then reduced to two; changes in color-tone and in saturation, the latter including admixtures of both white and black (Hillebrand; Hering, *A*, 51 ff.).

In this group of experiments it has seemed best to follow the better known terminology, though Hering's conception of the matter ought not to be disregarded.

Light and Color in General.

135. Color-Blindness, Holmgren's Method. *a.* Spread the worsteds on a white cloth in good daylight. Pick out a pale green (i. e., a little saturated green) that leans neither toward the blue nor the yellow; lay it by itself and require the person under examination to pick out and lay beside it all other skeins that are colored like it, not confining himself, however, to exact matches, but taking somewhat darker and lighter shades also, so long as the difference is only in brightness and not in color-tone. Do not tell him to pick out "the greens" nor require him to use or understand color words in any way; simply require the sorting. If he makes errors, putting grays, light browns, salmons, or straws [1] with the green, he is color-blind; if he hesitates over the erroneous colors and has considerable difficulty, his color-vision is probably defective, but in a less degree.

b. If the experimentee makes errors, try him further to discover whether he is "red-blind" or "green-blind" by asking him to select the colors, including darker and lighter shades, that resemble a purple (magenta) skein. If he is red-blind, he will err by selecting blues or violets, or both; if he is green-blind, he will select green or gray, or both, and if he chooses any blues and violets, they will be the brightest shades. If he makes no errors in this case, after having made them in the previous case, his color-blindness is incomplete. Violet-blindness is rare. See also Ex. 141 *b*.

Complete certainty in the use of even such a simple

---

1 It is difficult to give the tints accurately in words. The experimenter should consult the colored charts given in the works of Jeffries mentioned in the bibliography, and in Rayleigh, *B*.

method as this is not to be expected without a full study of it and experience in its application. Helmholtz, Hering, König, Kirschmann, and others give exact methods for determining the particular colors that are lacking in the vision of the color-blind.

On color-blindness and methods of testing for it, see Helmholtz, *A*, 357–372, 456–462; Fr. 388–399, (294–300, 847–848); Holmgren; Jeffries, *A* and *B*; Rayleigh, *A* and *B*; Hering, *H*, *I*, *N*, Hess, *B*; Abney, *A*; Abney and Festing; König, *B* and *C*; Brodhun, *A* and *B*; König und Brodhun; König und Dieterici, *A*; Schuster; Preyer; Donders, *C*; Kirschmann, *A*; Pole.

136. Vision with Peripheral Portions of the Retina: Perception of Light. A very faint light often appears brighter when its image lies not in the *fovea*, but a few degrees away from it. If no increase of brightness is observed, it is at least difficult to trace any decrease in brightness till the image is many degrees from the *fovea*. This experiment is most easily made at night with faint stars. In the laboratory it may be made with the dark box. On the rear wall of the box place in a horizontal line three bits of white paper of equal size, at such distances that the line of sight moves through an angle of ten degrees in turning from the middle one to either of the outer ones. Make a pin-hole above and below the middle piece, distant from it about an inch, and cover the holes on the outside with paper till the holes are barely visible after the eye has been some time adapted. These bright points serve to steady the eye. The eye should not, however, be directly fixed upon them, but at a point midway between them. Reduce the illumination of the box to a minimum (e. g., to the amount of light that would enter through a pin-hole covered with one or more pieces of porcelain or translucent cards), wrap the head and the end of the box in an opaque cloth, and allow the eyes to become adapted to the darkness,

looking from time to time for the shimmer of the papers at the back of the box. Full adaptation requires a long time, but fifteen minutes is sufficient in this case. By degrees, if the illumination is of the right intensity, the papers will be seen very faintly. If the eye is turned directly towards one of them, it often disappears in the retinal light while the others brighten. Fixate each of them successively, and compare its brightness with the others; fixate also other points in the field so as to bring the images upon different quadrants of the retina. Close the eyes from time to time to renew the adaptation, and avoid observations when the retinal light is strongly concentrated in the centre of the field.

On the results of such experiments as this, and on the explanation of the phenomenon observed, experimenters are somewhat at variance, but see Helmholtz, *A*, 268; Aubert, *A*, 495, *B*, 89 ff.; A. E. Fick, *B*; Kirschmann, *B*; Treitel, and the literature cited by them.

137. Vision with Peripheral Portions of the Retina: Perception of Color. The distribution of the sensibility of the retina for color is unlike that for light. At the very centre the pigment of the yellow spot itself interferes somewhat with the correct perception of mixed colors (see Ex. 115). In a zone immediately surrounding this all colors can be recognized. Outside of this again is a second zone in which blue and yellow alone can be distinguished, and at the outermost parts not even these, all colors appearing black, white, or gray. The zones are not sharply bounded, but blend into one another, their limits depending on the intensity and area of the colors used. The fixing of the boundaries of the zones of sensibility is known as perimetry or campimetry.

a. With the apparatus at hand, find at what angles from the centre of vision on the vertical and horizontal meridians

of the eye the four principal colors, red, yellow, green, and blue, can be recognized; try white also. Keep the eye steadily fixed on the fixation mark of the instrument, and have an assistant slide the color (say a bit of colored paper 5 mm. square pasted near the end of a strip of black cardboard an inch wide) slowly into the field from the outside. It will be well to move the paper slowly to and fro at right angles to the meridian on which the test is made, so as to avoid retinal fatigue. Take a record of the point at which the color can first be recognized with certainty. Repeat several times and average the results. The size of the colored spot shown should be constant for the different colors, and the background (preferably black) against which the colors are seen should remain the same in all the experiments.

b. Repeat the tests with colored squares 20 mm. on the side, and notice the earlier recognition of their color as they approach from the periphery.

c. Try bringing slowly into the field (best from the nasal side) bits of paper of various colors, especially violet, purple, orange, greenish yellow, and greenish blue; or better, hold the bit of paper somewhat on the nasal side of the field and turn the eye slowly toward it, beginning at a considerable angle from it. If the paper is held before a background containing a line along which the eye can approach the paper, the eye will be assisted in making the approach gradual; the apparatus used in Ex. 113 *b* can easily be adapted for this purpose. Observe that on the outer parts of the retina these colors first get their yellow or blue components, and only later the red or green. If the range of choice is sufficiently large, it may be possible to find a red (inclined toward red-purple) and a green (inclined toward the blue), which, like pure blue and yellow, change only in saturation and not at all in color-tone as they move inward

toward the centre of the field. These four colors are the *Urfarben* or primary colors of Hering.

Helmholtz, *A*, 372–374, Fr. 399–400; Hess, *A*; Hering, *G*, *L*; A. Fick, *A*, *B*, 206 ff.; A. E. Fick, *B*, 479 ff.; Aubert, *A*, 539–546, *B*, 116 ff.; Kirschmann, *C*.

138. Changes in Color-Tone. In the spectrum, change of wave-length, if not too small, is accompanied by change of color-tone. The change is most rapid in the yellow-green and blue-green regions of the spectrum, less rapid toward the ends, and at the extreme ends the only changes are those in brightness. With the spectroscope and daylight find the characteristic Fraunhofer lines *D*, *E*, *F*, *G*, and *H*. The *D* line lies in the golden yellow, *F* in the greenish blue, and *H* at the end of the violet. Between *D* and *F* the wave-length changes from 589.2 to 486.1 $\mu\mu$ (from 5.092×10^{14} to 6.172×10^{14} vibrations per second), and the color runs through yellow and green to blue, while from *F* to *H* with the nearly proportional change in wave-length from 486.1 to 393.3 $\mu\mu$ (from 6.172×10^{14} to 7.628×10^{14} vibrations per second) the change is only from greenish blue to violet. Notice the region from near the line *G* to the end of the spectrum which shows little change in color-tone and a similar region of uniform color-tone at the red end. Notice also the tendency of the succession of spectral colors to return upon itself, shown in the resemblance of the violet and red.

Helmholtz, *A*, 289,320, Fr. 319 (237); Wundt, 3te Aufl., I., 449 f., 4te Aufl., I., 485 f.; A. Fick, *B*; Aubert, *A*, 530 f. On just observable changes in color-tone, see B. O. Peirce, Jr., König und Dieterici, *B*, Brodhun, *A*, and the literature there cited.

139. Changes in Saturation. These are easily shown on the color-mixer. Make a succession of mixtures of red and white, beginning with a proportion of white that just changes the red, and increase the proportion till no effect of red remains. At first use a small disk of red laid on

over the larger disks as a sample with which to compare the mixtures. Toward the end of the experiment exchange the red for a small white disk. Notice the changes of color-tone that are to be observed, especially when the amount of color is small. Try similarly with the other chief colors. According to Rood, who worked with the color-mixer, yellow-green and violet are unchanged; Helmholtz's results with spectral colors are somewhat different.

Changes in saturation can also be made by adding gray of any shade instead of white. The whole range of mixtures can be shown on a single disk, like that in Ex. 141, by painting the star upon a white or gray ground, or by pasting a star of colored paper on such a ground. With white, however, the rays of the star must be given a leaf shape, or the color will fall off too rapidly from the centre.

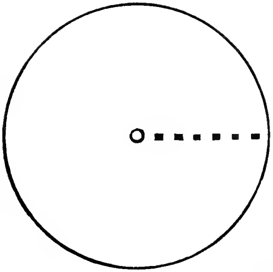
Helmholtz, *A*, 322, 470–471, Fr. 369 (281); Aubert, *A*, 531–532; Rood, *A*, 39–40, 194–201; Nichols, *A*.

140. Changes in Intensity: Black and White. Black and white are the extremes of intensity in the series of grays. The ordinary black and white of conversation are, however, considerably short of these extremes.

a. Compare a bit of black velvet or of black cardboard with a still deeper black by holding it in front of the opening in the dark box. Compare, also, ordinary white paper in diffused light with the same in direct sunlight, or with a brightly illuminated white cloud.

b. Just observable differences with medium intensities. Prepare a disk like that shown in the accompanying cut by drawing along a radius of a white disk a succession of short black lines of equal breadth. Let the breadth of the line correspond to about one degree on the edge of the disk. Since the breadth of the line is everywhere the same, it will occupy a relatively greater angle as it nears the centre.

When the disk is set in rapid rotation, each short line will give a faint gray ring, those at the outer edge being very faint, those nearer the centre, darker. Find which is the faintest ring that can be seen, and calculate the proportions of black and white in it.[1] The ratio of black to white measures approximately the just observable decrease in intensity below the general brightness of the disk. The results of Helmholtz and Aubert are respectively: Helmholtz, 1 : 117 to 1 : 167, Aubert, 1 : 102 to 1 : 186, the differences depending on the intensity of the general illumination of the disk. Some wandering of the eyes is helpful, but too rapid motions which tend to break up the even gray of the rings must be avoided. It is absolutely essential that the rotation be very rapid and perfectly free from vibration — so rapid that with moderate motions of the eyes the uniform gray of the rings is not disturbed. If great rapidity is impossible, replace the single black line by two of proportionately less breadth on opposite sides of the disk, or by four at 90°.



c. With these very faint rings a disappearance and reappearance is to be observed somewhat like that found for

---

[1] The formula for the amount of black, assuming that the radial line is absolutely black, and taking some arbitrary point, e.g., the middle, for calculation, is of course $\frac{b}{2\pi r}$, where b is the breadth of the radial line, and r the distance of the chosen point from the centre of the disk. The black of the lines is not quite absolute, even when the blackest black paint is used. The differences in sensation are therefore smaller than those shown by the calculation.

just audible sounds in Ex. 61 *b*. The observation is most conveniently made, according to Pace, on a disk of the following dimensions: diameter of disk, 20 cm., width of radial line, 5 mm., length of the short lines, 5 mm., spaces between the short lines, 8 mm., distance of innermost short line from the centre of the disk, 17 mm.

Helmholtz, *A*, 384–393; Fr. 411–419 (310–316); Aubert, *A*, 487–492; on *c*, Pace. For references on the just observable difference of intensity with different standard intensities, see the chapter on Weber's Law below.

141. Changes in Intensity: Colors. At their maximum intensity all colors tend toward white or yellowish white. Red, however, hardly gets beyond the yellow; green becomes first yellow, then white, while blue and violet easily reach it. At their minimum intensity all colors appear gray or black.

a. The maximum intensity may be observed with spectral colors, though not entirely homogeneous ones, with a prism placed in the sunlight so that it throws an extended spectrum on the wall. Hold a card, pierced with a pin-hole, before the eye, and bring the eye successively into the different colors, looking meanwhile at the prism. Something of the same kind may be seen by looking through pieces of colored glass at the disk of the sun behind a cloud (in which case the portions of the cloud seen at the sides of the glass afford a means of comparison), or at the image of the sun reflected from an unsilvered glass plate, or by concentrating light from colored glass on white paper with a convex lens.

b. The minimum intensity with spectral colors may be observed with a spectroscope. Adjust the instrument so that the chief Fraunhofer lines can be seen, and then place, as a source of light, at a little distance from the slit of the instrument, a screen covered with dark gray paper or black velvet. Though no color remains, a little light can be made

out — brightest in the region before occupied by the green. The observer must envelop his head and the ocular of the instrument in an opaque cloth, and allow time for the adaptation of his eye. This colorless spectrum probably represents what is seen by a totally color-blind eye.

Von Bezold, with whom this experiment originates, observed with gradually decreasing intensity a falling out of the yellows and blues before the final stage of colorlessness was reached. König doubts whether the red ever loses its color entirely.

With pigment colors a convenient way is to paste equal squares of colored papers upon a piece of cardboard, and then to place the whole in the dark box, and gradually reduce the illumination, or starting with the illumination at zero, gradually increase it. Try with both black and white cardboard as background. For demonstrational purposes a disk like that in the accompanying cut (in which the shaded part stands for color, and the solid black for black) may be used and the whole series of intensities shown at once.[1]

Helmholtz, *A*, 402–444 ; A. Fick, *B*, 200–202 ; Aubert, *A*, 532–536 ; Rood, *A*, 181–194 ; C. S. Peirce. On *a*, Helmholtz, *A*, 284–285, 465–466, Fr. 315 (234); Brodhun, *B*. On *b*, Helmholtz, *A*, 469, 471–

[1] Since the black of the disk is really a very dark gray, and would thus make a change in saturation, this is not an absolutely pure experiment, but is sufficiently exact for showing the general effect of darkening. If a practically perfect black is desired, it may be had, following Rood, by making the colored star rotate before an opening into a dark room or a suitable dark box.

472; von Bezold, *A*; Ebert; Abney and Festing; König, *A*, 354 ff., where other literature is cited.

For measurements of the just observable difference of intensity for different colors, see Helmholtz, *A*, 402–415; Aubert, *A*, 531; A. Fick, *A*, 177; and the references given by them.

142. Purkinje's Phenomenon. In a light of moderate brightness choose a bit of red paper and a bit of blue paper that are of about equal intensity and saturation, carry both into full sunlight and notice which appears brightest; carry both into a darkened room, or place them in the dark box and compare them again. If a dark room or box is not at hand, observe them through a fine pin-hole in a card, or even with nearly closed eyes.

Helmholtz, *A*, 428–430, 443–444, Fr. 420–425 (317–321); Hillebrand; König, *A*; Charpentier, *A*, 227 ff., 335 ff.; Rood, *A*, 189 ff.

143. Size of the Colored Field. When the retinal area stimulated is very small, colored surfaces appear colorless, with ordinary intensities of illumination. When somewhat larger they may appear colored, but not necessarily in their true color-tone. The background against which they are placed is also important.

a. On pieces of black and white cardboard, paste small squares of several kinds of colored paper, one series 5 mm. square, one 2 mm. square, and one 1 mm. square. Walk backward from them and notice their loss of color. Observe also the changes in color-tone.

b. A number of retinal impressions, even when not contiguous, are mutually supportive in color effect. This is conveniently shown in the indirect field. In a two-inch square of black cardboard, punch sixteen holes arranged in the form of a square, four rows of four holes each. The holes should be an eighth or three-sixteenths of an inch in diameter, and be separated by spaces of the same extent. Paste upon the back of the square a piece of red paper of

sufficient size to cover the holes, thus making of them sixteen little red circles. Prepare also another piece of black cardboard of such shape that it may be laid over the square and cover all the holes except one of the corner ones, and again when necessary may easily be removed.

With the apparatus used in Ex. 137, find the point on the nasal half of the retinal horizon where the single red circle can just no longer be seen in its true color. In making this determination, the square should be so held that the diagonal to which the uncovered circle belongs is horizontal. When the point has been found, uncover the remaining fifteen circles (all farther toward the periphery), and notice that the color of the group can be seen distinctly. Fatigue in fixing the limit at which the circle can be seen should be avoided.

On *a*, Helmholtz, *A*, 374–375, Fr. 399–400 (300); Aubert, *A*, 536–539; Hering, R, 18. On *b*, A. E. Fick, *A* and *B* (especially 451–452).

144. Duration of Illumination. Fechner's Colors. The retinal inertia is different for different colors. In the experiments on after-images (Ex. 125 *d*), it was observed that the after-image of a white surface faded away through a succession of colors; a succession of colors appears also to result from a very brief vision of a white surface. This can be seen upon almost any slowly rotating disk of black and white; those used in Exs. 128 *b* and 145 *c* show the colors well, and that in Ex. 145 *a* shows something of the dependence of particular colors upon particular rates of recurrence. Rotate any of these disks with less rapidity than that required for a uniform gray, and, keeping the eyes steadily fixed upon some point of its surface, notice both the advancing and the retreating edges of the white portions of the disk. The colors may not appear instantly, but are not difficult to get with attentive gazing.

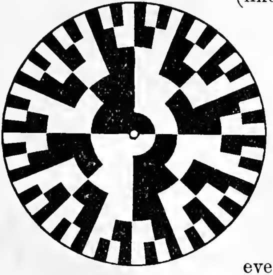
Very striking and beautiful effects can be obtained by

substituting for the black and white disk a black one from which narrow sectors have been removed. This pierced disk is rotated before a brightly lighted background, e. g., a sheet of white cardboard in full sunlight, a bright cloud, or the clear sky, and the eye is brought very close to the disk.

Helmholtz, *A*, 530–533, Fr. 500–504 (380–383); Fechner, *A*; Brücke; Exner; Aubert, *A*, 560; Rood, *A*, 92 ff., *B*; Nichols, *B*; Charpentier, *B* and *C*.

145. Rate of Rotation Required for a Uniform Blending of Black and White. All blending of colors by rotation depends on the phenomenon of positive after-images (Ex. 125). A disturbance once set up in the retina does not at once subside, but continues an instant after the removal of the stimulus. If stimuli follow in sufficiently rapid succession the disturbances fuse, and the result is the same as if the stimuli had been mixed before reaching the retina. A rough determination of the rate required for uniform blending may be made with the color-mixer and a metronome.

a. Place the color-mixer in such a position that the disk (like that in the margin) shall be illuminated by diffused daylight only. Turn the driving-wheel slowly and ascertain, by counting, how many turns of the disk correspond to one turn of the driving-wheel. Start the metronome, and turn the driving-wheel in time to its beats, making a turn every one, two or four beats.

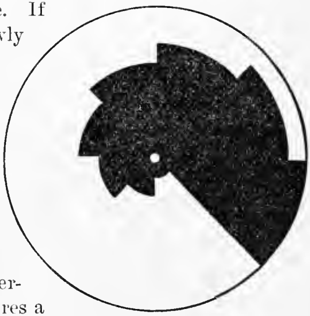


Notice which of the rings, if any, is just blended into a uniform gray. If none is just blended, change the rate of

the metronome a little, and repeat the trial till such a one is found. From the rate of the metronome, the number of turns of the driving-wheel, and the number of white sectors in the just blended ring, find the number of stimuli per second required. The experiment is easier when two observers work together, one giving his attention to the regular driving of the color-mixer, and the other to watching the disk. The driving-belt of the instrument must be tight enough not to slip, and the metronome should be kept well wound up. Its scale should also be verified by counting with a watch. The observer must of course avoid eye motions which break up the uniformity of the gray.

b. Repeat the determination with the disk in direct sunlight; also in a partially darkened room or at twilight.

c. A disk like that in the margin shows mixtures of several different proportions of black and white at once. If such a disk is brought slowly to the rate just necessary to give a uniform gray at the centre, a little flickering can still be traced in the outer rings. Care should be taken not to fixate the middle of the disk exclusively, for with moderate illumination the periphery of the retina requires a little greater speed for uniform



blending than the centre. Helmholtz states that little difference is to be observed in the rate at which the flickering ceases with the somewhat similar disk shown at the left in

Ex. 152 *d*, but with that given here, it is believed that careful observation will not fail to show a difference.

Helmholtz, *A*, 488 ff., Fr. 453 (344) ff.; Aubert, *A*, 517; A. Fick, *B*, 211–222; Nichols, *B*; Bellarminow and the literature cited by him.

146. The Talbot-Plateau Law. This law may be stated as follows: When once the rate of rotation is sufficient to give a uniform sensation, the color and brightness of any given concentric ring of the disk are the same that they would be if all the light reflected from it were evenly distributed over its surface, and no further increase in rapidity produces any effect upon its appearance. Rotate the disk used in Ex. 145 *a*, and increase the rapidity till the innermost portion gives a uniform gray. When this appears, the rate of recurrence in the outermost ring is 32 times more rapid than in the innermost, and yet no difference in shade is to be seen. To show that the gray is actually of the same brightness that would come from an even distribution of the light reflected from the whole surface of the ring, prepare a disk with many equal black and white sectors — 32 or more of each. Place the disk on the color-mixer, and look at it when at rest through a double convex lens of short focus (e.g., 1 in.), held at such a distance from the eye and disk that no distinct image is formed, but the field of the lens appears an even blur of gray. Now put the disk in rapid rotation and notice that the gray remains unchanged.

The result of these experiments would be the same were other colors substituted for black and white.

Helmholtz, *A*, 482–485, Fr. 446–450 (338–341); Aubert, *A*, 515–516; Talbot; Plateau.

147. Brücke's Experiment. When the rate of rotation is insufficient to produce an even blending, the brightness

of the disk is influenced by the rate. Set the disk used in Ex. 145 *a* in rapid enough rotation to blend the innermost ring, and then let it gradually come to rest. As it turns more and more slowly, there will be observed in one ring after another, beginning with the innermost, just as it loses its uniform character, a notable brightening. The white sectors now have opportunity to produce their full effect upon the retina before they are succeeded and their impression cut off by the black sectors.

Helmholtz, *A*, Fr. 455–456; Exner; Aubert, *A*, 510.

COLOR MIXING.

148. Mixed Colors. Experiments upon this subject cannot be regarded as entirely satisfactory except when made with pure (homogeneous) spectral colors. The colored papers with which the following experiments are made show anything but homogeneous colors, as can easily be seen by looking at scraps of them on a dark background through a prism. They produce the same mixture effects, however, that spectral colors of the same tone, intensity, and saturation would produce; and the great facility of their manipulation on the color-mixer recommends them for preliminary experiments and for illustrative purposes.

Three colors properly selected serve to produce by their mixtures all the intermediate colors (though in most cases in less saturation) with purple and white (i. e., gray) in addition. The colors generally selected are red, green, and blue or violet. Green cannot be mixed from colors that themselves do not resemble it; i.e., it can be mixed from yellow-green and blue-green, but not from yellow and blue, and not in anything like full saturation.

The general facts of color mixing, together with the method of representing them in a two dimensional diagram, were first discovered by Newton, and are sometimes desig-

nated by the general term of Newton's Law. For the methods of constructing such diagrams, see, among others, Helmholtz, *A*, 334 ff., Aubert, *A*, 524 ff., and Rood, *A*, 218 ff., 224 ff.

a. Mix a yellow from red and green on the color-mixer. The yellow produced will be dark, and, as a test of its hue, should be matched with a mixture of yellow and black made with smaller disks set on above the first. In the same way mix a blue from green and violet that shall match a mixture of blue and black (or blue, black, and white).

b. From red and violet or blue, mix several purples between violet and red.

c. From red, green, and violet, mix a gray that shall match a mixture of black and white on the small disk. In such a case as this it is highly probable that the gray appears, because the combined colors furnish among them light of all wave-lengths in about the proportions in which they occur in ordinary white light. With the homogeneous red, green, and violet of the spectrum, the case would of course be different. To avoid troublesome after-images, the adjustment of the disks should be left to an assistant, or the observer should wear dark glasses, except when the disks are in revolution at full speed.

If the colored disks used in these experiments are not opaque, several should be used at once instead of a single one.

For demonstrational purposes mixtures of two colors in different proportions can be shown on a single disk of the star form (see Ex. 141) by painting the star in one color and the ground of the disk in another (or by pasting colored papers instead of painting), but in either case some trial will be necessary to determine the proper shape for the rays.

Helmholtz, *A*, 311–316, 320–322, 325–333, 375, 376–473, 485, Fr. 359–365, 367–369, 450 (272–277, 279–281, 341); Aubert, *A*, 521–524; Hering, *M*; Maxwell, *A* and *B*; Rood, *A*, 124 ff.

149. Complementary Colors. The combination of red, green, and violet mentioned in the last experiment is not the only combination that gives white or gray. For every color there is another or complementary color, which, mixed with it, gives a colorless combination. Some of these pairs are red and blue-green, yellow and indigo-blue, green and purple, blue and orange, violet and yellow-green.

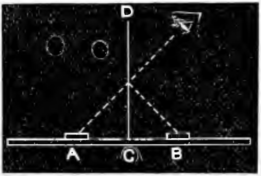
a. Try several of these pairs upon the color-mixer, matching the resultant gray with a mixture of black and white on the small disk. It will probably be found in some cases that no possible proportions of the colored papers at hand will give a pure gray. In that case a little of the color complementary to that remaining in the gray must be added. Suppose the red and blue-green papers, when combined, give gray with a tinge of brown (i.e., dark orange); a certain amount of blue must then be added to compensate. For example, with certain papers 180° of blue-green + 36° indigo-blue + 144° red make a gray that matches 90° white + 270° black. To see the true complement of the red used, it is then necessary to prepare a disk carrying green and indigo in the proportions of 180 and 36; i.e., 300° blue-green, 60° indigo. In the same way the complement of the blue-green used is a bluer red than that of the red paper, and may be seen by itself by mixing 288° red with 72° indigo. It is very important here, and in all cases where a resultant white or gray is to be observed, to have some undoubted white or gray in the field to prevent mistake in very faint tinges of color.

The criticism made upon Ex. 148 *c* applies here with equal force. To be conclusive, the experiment must be made with far simpler colors than those of colored papers.

b. Negative after-images, when projected on a white surface, are seen in colors approximately complementary to those that give rise to the after-images. Compare complementary colors found in this way with those found on the color-mixer.

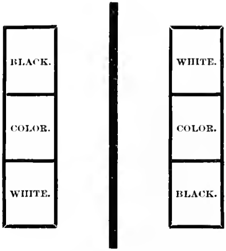
Helmholtz, *A*, 316–319, Fr. 365–367 (277–278); Aubert, *A*, 521–524; König und Dieterici, *A*, 284 ff. ; Rood, *A*, 161 ff.

150. Other Methods of Mixing Colored Lights. *a.* Lambert's Method. The Reflection Color-Mixer. This is the simplest of all the methods. The colors to be mixed are placed on a suitable background (e. g., a smooth surface of black velvet), on opposite sides of a vertical glass plate. The eye is brought into such a position that the reflected image of the color on one side appears to overlie that seen by transmission on the other side. The glass must of course be of good quality and clean. The relative intensity of the colors can be varied by varying their distance from the glass. Bringing the colors near the glass, or raising the eye, strengthens the reflected and weakens the transmitted light. Strips of colored paper placed with their ends next the glass, provided the illumination is equal, will show an even blending of the colors through a considerable range of intensities, one color predominating at one end of the combined image, the other at the other end.



By substituting a bit of glass on a black background for one of the colors, and then placing the instrument so that a portion of clear sky may be reflected in the glass, it is possible to mix sky-blue with its complement, or with any other color.

To mix two colors in equal proportions, arrange them with black and white, as in the diagram below. Adjust the glass (or the position of the eye) till the grays made by the black and white at the ends exactly match; the colors will then be mixed in equal proportions.

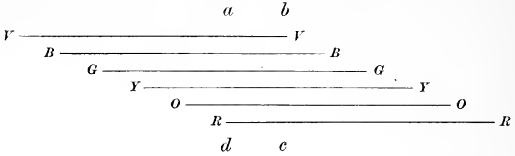


GLASS.

b. Mixture by Double Refraction. Colored areas placed side by side appear mixed when regarded through a double refracting prism. The prism doubles both fields, and causes a partial overlapping. In the overlapped portion the colors are mixed, each color being present in the mixture at approximately half its original brightness. The prism should be achromatic.

c. Mixture of Spectral Colors. Fine mixtures may be obtained with a prism and Figs. 1, 2, and 3 of Plate I.; or, still better, from figures shaped like these, but in white upon a black ground. Since a prism refracts different kinds of light in different degrees, it produces a multitude of partially overlapping images of a bright object, which appear to the eye as colored fringes. (Observe through a prism held horizontally, an inch square of white paper on a black background.) These overlapping images may be illustrated by the following diagram, in which the horizontal lines stand for the

images, and the capital letters for the colors of the light producing them.



In the area *a b c d* all the images overlap and the white of the paper is still seen. Toward the left from *a*, however, the different kinds of light gradually fail, beginning with the red. The successive colors from greenish blue to violet result from the mixture of what remains. At the other end a similar falling away of the colors gives the succession from greenish yellow to red. In Fig. 1, the spectra seen on the upper and lower edges of the inch square of white paper are brought side by side; on one side red, orange, and yellow, and on the other greenish blue, blue, and violet. The colors that stand side by side are complementary pairs, both in tone, intensity, and saturation; for the greenish blue is the white of the paper less the red, and the blue the same less the red, orange, and yellow, and so with the rest; and if the two spectra be exactly superposed, as can be done with an adaptation of the method of *b* above, they will make precisely the white from which they originated.

If a very narrow strip of white upon a black ground is looked at through the prism, the images overlap less and another color appears; namely, green, as may be seen in Fig. 2 on the narrow white band between the black bars. When, on the other hand, a narrow black band on a white ground is taken, the spectrum of the white surface above and of that below partially overlap, and give another set of mixtures. If the diagram is held near the prism at first, and

then gradually withdrawn from it, the advance and mixing of the spectra can easily be followed. Besides the greenish yellow at one end and the greenish blue at the other, there are a rich purple, complementary to the green beside it, and a white between the purple and the greenish yellow. The last is a white produced by the mixture of the blue of one spectrum with the complementary orange-yellow of the other.

Fig. 3 shows a number of color mixtures with different proportions of the constituents. In the spectra from the white triangle appear mixtures of each color in the spectrum seen on the white band in Fig. 2, with every other color found there. Upon the black triangle the spectra from the white edges above and below show mixtures similar to those on the black band in Fig. 2. The diagram should be placed at such a distance that a little of the white and black triangles can still be seen.

Helmholtz, *A*, 350–357, 485, 491–493, Fr. 402–407, 450, 458–461 (303–306, 341, 347–349); Aubert, *A*, 521–524; Maxwell, *A*; Rood, *A*, 108 ff., 124 ff.; Hering, *O*; von Bezold, *B*, 77 ff. On *a* and *c*, Benson. On refined methods of mixing spectral colors, see especially the first reference to Helmholtz.

CONTRAST.

The effect of one color on another, when not mixed with it, but presented to the eye successively, or simultaneously in adjacent fields, is known as contrast. Two kinds are distinguished, *Successive contrast* and *Simultaneous contrast*. The color that is changed or caused to appear upon a colorless surface, is known as the *induced color;* the color that causes the change is called the *inducing color*. Successive contrast is largely a matter of negative after-images, and their projection upon different backgrounds, and is universally regarded as a matter of physiology. Simultaneous contrast, on the contrary, has been regarded by Helmholtz and his

supporters as a matter of psychology, as a sort of misjudgment. The studies of the last few years, however, chiefly those of Hering, have demonstrated that simultaneous contrast also in most, and probably in all cases, is physiological, a phenomenon of the retina (and its central connections), not of mistaken inference.

151. Successive Contrast. *a.* Prepare a set of colored fields of the principal colors, including white, black, and gray, say 3 x 5 inches in size, and some small bits of the same colors, say 1 cm. square. Lay a small square on the black field, get a strong negative after-image, and project it first on the white and then on the other fields. Notice that the color of the after-image spot is that of the field on which it is projected, minus the color that produced the spot; e. g., the after-image of red projected on violet looks blue, and on orange looks yellow. Or, to say the same thing in other words, the color of the spot is a mixture of the color of the after-image with the color of the ground upon which it is projected. Thus a blue-green after-image when projected on violet, gives blue; when projected on orange, gives yellow. Notice that when the image is projected on a field of the inducing color it causes the spot on which it rests to look dull and faded; but when it is projected upon a field of complementary color, it makes the spot richer and more saturated. Indeed, it is only by first fatiguing the eye for one color and then looking at its complement that the most saturated color sensations can be produced. In general, colors that are complementary, or nearly so, are helped in appearance by contrast; those that resemble each other more nearly are injured.

b. These effects, in even greater brilliancy, can be seen by laying the small square of color directly on the larger colored surface, staring at it a few seconds, and then suddenly puffing it away with the breath. See also Ex. 134.

c. This contrast effect may be so strong as actually to overcome a moderately strong objective color. Place a small piece of opaque orange paper in the middle of a pane of red glass and look through the glass at a clear sky or bright cloud. The strength of the induced blue-green will be sufficient to make the orange seem blue. See also Ex. 124 *d*.

Helmholtz, *A*, 537–542, Fr. 510–515 (388–392); Hess, *C*; Rood, *A*, 235 ff.

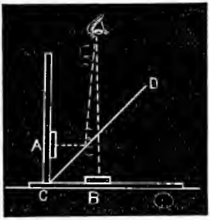
152. Mixed Contrasts. When special precautions are not taken to exclude successive contrast, both successive and simultaneous co-operate in the general effect. Some of the results are striking and beautiful.

a. Colored Shadows. Arrange two lights so that they shall cast a double shadow of a pencil or small rod upon a white surface. The daylight will answer for one light if it is not too strong, but it must not be forgotten that unless the light comes from an overcast sky it will be blue. Introduce different colored glasses one after another before one of the lights, and notice the beautiful complementary color that immediately appears in the shadow belonging to that light. The brightness of the two lights should be so regulated that the shadows shall be about equally dark when the colored glass is introduced before one of the lights. See also Ex. 155.

Use a blue glass, and adjust the relative intensities of the lights so that the yellow shadow appears at its brightest, and notice that it seems as bright as the surrounding blue, or even brighter. As a matter of fact, however, it receives less light than the surrounding portions; for in order to be a shadow, it must be a portion of the field from which the light is partly cut off.

b. Mirror Contrasts. Ragona Scinà's Experiment. Place upon the horizontal and vertical surfaces of the instrument

white cards carrying black diagrams.[1] The diagrams being in place, hold between the two at an angle of 45° a pane of colored glass, say green, and observe that the black of the horizontal diagram seems tinged with the complementary color, that is, purple. This contrast color may often be improved by slightly altering the inclination of the glass, or by changing the relative illumination of the diagrams by interposing a colorless screen between one or the other of them and the source of light, or by shifting the whole instrument. This experiment will be readily understood after



a consideration of the accompanying cut. The glass plate is represented by *C D*, the black portion of the vertical diagram by the projection opposite *A*, that of the horizontal diagram by the projection at *B*. The light reaching the eye from the white portion of the horizontal diagram is colored green by the glass; that from the white portion of the vertical diagram is reflected from the upper surface of the plate, and is therefore uncolored.[2] The mixture of the two gives a light green field. For simplicity, we may assume that no light comes from the black portions of the diagram. Then in the portion of the light green

[1] Any black spot will answer. For this experiment diagrams made up of sets of heavy concentric black rings, lines a quarter of an inch wide, separated by white rings of triple width, give an excellent effect. The diameters should be so chosen that a black ring on the horizontal diagram shall correspond to a white one on the vertical and *vice versa*, and shall appear to lie in the midst of the white when the diagrams are combined in the way described above. A pair of diagrams made up of parallel black bars, a quarter of an inch wide, separated by quarter inch spaces, and so placed in the instrument that they give a checkerboard pattern when combined, are useful for keeping in the field a true black with which the changed colors can be compared.

[2] As a matter of fact, a small portion is also reflected from the lower surface of the glass, and contributes a minute amount of green.

field corresponding to the black of the vertical diagram, the white component will be wanting and the green will appear undiluted; in the portion corresponding to the black of the horizontal diagram, the green component will be wanting and the faint white (i. e., gray) should appear by itself. It does not, however, because of the contrast color induced upon it. As a matter of fact, the black portions are not absolutely black; the small amount of light that comes from them tends on one hand to make the green image (image of the black of the vertical diagram) a little whiter, and on the other hand to counteract the contrast in the purple image by adding to it a little green. Try the experiment with other glasses than green.

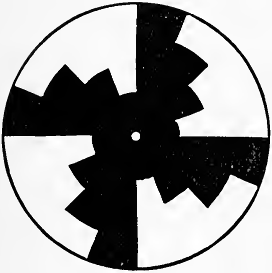
Another form of the mirror contrast experiment is as follows. Place a mirror where the sky or a white surface of some kind will be seen reflected in it. Lay upon its surface a plate of colored glass (green for example), and hold a little way above it a narrow strip of black cardboard or a pencil. Two images will be seen: one a vivid green, the other a complementary purple. The green image belongs to the surface reflection of the colored glass, as may be proved by observing that when the strip of cardboard touches the surface, the green image touches it also. The purple image belongs to the reflection from the back of the mirror. It is easy, by substituting a gray strip for the black, to show that contrast can suppress a weaker objective color actually present.[1]

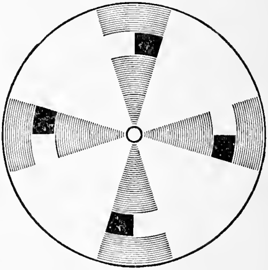
c. Meyer's Experiment. Lay on a large colored field a small piece of gray or even black paper (e.g., 1 cm. wide by 2 cm. long), and cover the whole with a piece of semi-transparent white paper of the same size as the colored field. The contrast color will appear on the gray paper.

[1] For fuller explanation with diagram, see *American Journal of Psychology*, V., 1892–93, 407, and von Bezold, 154 f.

If thin tissue paper is used, more than one thickness may be needed for the best result. Paper mats, woven one way of gray paper and the other of colored, show this contrast beautifully. They may easily be made from kindergarten materials.

d. Mixed Contrasts with the Color-mixer. Disks made on the pattern of the cut at the left show beautiful contrasting





grays. The disk used in Ex. 145 *c* shows a longer series, but requires a more rapid rate of rotation. The same can be shown also by laying a number of small sheets of tissue paper over one another in such a way that they partially overlap, making a portion where there is but a single thickness, and next it a portion where there are two thicknesses, and next that again one of three thicknesses, and so on. When the whole is held up to the light, the contrasts of adjacent portions are very easily seen.

Contrast colors can be shown finely with disks like that in the cut at the right, in which the shaded portions represent color, the black portions, black, and the white, white. A little care is necessary in fixing the proportions of the color to white and black in the disks, but in general the

brightness of the gray should be about that of the color. When the contrast color has been satisfactorily obtained, bring near it a piece of white cardboard (e.g., 3 x 5 in.), so held with reference to the source of light that it appears about as bright as the contrast ring. Hold the card so that its shadow does not fall on the disk, or at least is out of sight. Notice the retreat of the contrast color from its edges. On such experiments as this much stress is laid by Helmholtz and the supporters of the psychological explanation of contrast.

Contrasts with two colors at once can be shown by making the inner portion of the colored sectors of one color, the outer portion of another. A temporary disk for showing contrast effects may be arranged by putting on the spindle of the color-mixer first a large colored disk (e.g., 20 cm. in diameter), then smaller combined disks of black and white (e.g., 12 cm. in diameter), and finally a still smaller colored disk (e.g., 10 cm. in diameter).

Helmholtz, *A*, 542 ff., Fr. 515–546 (392–417); Hering, *E*; Aubert, 496 ff., 546 ff.; von Bezold, 144–171; Rood, 241–272; Mayer.

For particular experiments, see the following: on *a* (second part), von Bezold, *B*, 153–154; on *b* (second part), Dove; on *c*, Meyer.

For quantitative measurements of contrast in grays, see Ebbinghaus, *B*; Lehmann; and Kirschmann, *D*.

153. Some of the Conditions that Influence Contrast.

a. Contrasts are stronger when the colors are near together. Lay a bit of white paper on a black surface, e.g., a piece of black velvet, and notice that the paper is whiter and the velvet blacker near the margin of the paper than elsewhere, notwithstanding that the eye moves about freely. This has received the name of "Marginal contrast" (*Randcontrast*).

On a piece of gray paper, the size of a letter-sheet, lay two strips of colored paper close side by side (e.g., pieces of

red and yellow or of green and blue, 1 cm. wide by 4 cm. long). Below them to the right and left, as far apart as the paper will permit, lay two other strips of the same size and color, red on the red side of the former pair, yellow on the yellow side. Notice the effect of the difference in distance on the contrasting pairs. Contrast of this sort is at a maximum when one color entirely surrounds the other.

b. Effect of size. When the area of the inducing color is large and that of the induced color is small, the contrast is shown chiefly on the latter; when the two areas are of about equal size, as in *a* above, the effect is mutual. Try with large and small bits of paper upon a colored field.

c. Borders and lines of demarcation that separate the contrasting areas tend to lessen the effect by excluding marginal contrast; and (since the eye tends to move along rather than across strongly marked lines), by hindering such motions of the eye as would bring about successive contrast. Repeat Ex. 152 *c*, using two slips of gray paper 5 mm. wide by 2 cm. long, and substituting a piece of moderately transparent letter-paper for the tissue paper. When the contrast color has been observed, trace the outline of one of the slips with a fine ink line upon the paper that covers it, and notice that the color nearly or quite vanishes. A disk like that in the cut accompanying Ex. 152 *d*, when provided with a second contrast ring, marked off on both its edges with a firm black line, shows a weakening of the induced color in the bordered ring.

This experiment and others like it play an important part in the psychological, as opposed to the physiological, explanation of simultaneous contrast; see Helmholtz, *A*, 543 ff., 559 f., Fr. 533 f., 539, 542, (406 f., 411, 414). Such a black border will, however, also make a weak objective color invisible.

d. Saturation. Contrast effects are generally most strik-

ing with little saturated colors. Compare the effect of increasing, decreasing, and extinguishing the second non-colored light in the colored shadow experiments. It is necessary, however, to see to it that reflected light from the walls and surrounding objects does not complicate the experiment.

Compare the intensity of the contrasts in Meyer's experiment (Ex. 152 *c*) before and after the application of the tissue paper. Notice also the part played by the white light mixed with the colored light in the mirror contrast experiments above. Try the effect of introducing white or black or both into the largest and smallest disks in the arrangement mentioned at the end of Ex. 152. Powerful contrasts with the most saturated colors can be observed, however, when the proper conditions are fulfilled.

e. Colors induced upon gray fields are stronger when the gray has about the same brightness as the inducing color. Repeat Meyer's experiment, using white paper instead of the gray or black. With the three disk arrangement try the effect of making the intermediate disk all white and all black. Rood finds that grays slightly darker than the inducing color are advantageous when the inducing color is red, orange, or yellow, and slightly lighter when the inducing color is green, blue, violet, or purple.

On conditions in general, see Helmholtz, *A*, 540–541, Fr. 513–514, (390–391), Kirschmann, *D*. In Hering, *E*, will also be found much on the effect of various conditions. On *b*, Exner, *B*. On *c*, Helmholtz, *A*, 546–547, Fr. 539–542 (411–414). On *d*, Helmholtz, *A*, Fr. 523–524 (399–400). On *e*, Rood, *A*, 261.

154. The Halo or *Lichthof* of Hering. Contrast is often to be seen in negative after-images. That observed in after-images of white objects on a dark ground has been adduced by Hering as an argument against the psychological explanation of contrast. Some of the simpler experiments are

as follows; for his development of them consult Hering, *A.*

a. Lay a half inch square of white paper on a large sheet of black cardboard (or better of black velvet), and put a small dot at its centre. Stare with unmoved eyes at the dot for from 15 to 30 seconds or more, then close and cover the eyes. There will then be seen, neglecting incidental color effects, the dark after-image of the paper surrounded by a halo of light, brightest next the paper and gradually falling off in brilliancy toward the periphery. This is explained on the psychological theory as due to contrast with the deep black of the after-image of the square. When, however, the converse of the experiment is properly made (a black square on a white ground), the dark halo which would be expected by contrast is not found, though the after-image of the black square is very bright.

b. Lay two white squares side by side two or three millimeters apart on the dark ground and between them a minute clipping of paper for a fixation point. Secure the after-images as before. The halos of the two squares coincide in the narrow space between and give a much brighter band in the after-image. Under favorable circumstances this bright band may remain visible while the after-images of the squares themselves are temporarily invisible. In both these experiments it is better to use both eyes than a single one. The explanation of the halo as a matter of false judgment, especially in the last mentioned case, is not easy.

Hering, *A.*

155. Simultaneous Contrast with Colored Shadows. The effects of simultaneous contrast are almost always lost in the more powerful ones of successive contrast. The first requisite, therefore, of an experiment on the first, is the exclusion of the second. This is not difficult for colored shadows.

a. Place a good-sized piece of white paper on a table in such a position that it may be illuminated at the same

time from a window (if the day is overcast) and from a gas-jet. Set upon it a small block or other object (about 5 cm. by 10 cm. in size); something black in color is best. Light the gas and observe the two shadows, one cast by the light from the window, the other by the gas. The first will appear yellowish, the second clearly blue.[1] Adjust the distance and position of the block with reference to the light so that the shadows shall appear about equally dark, and the blue shadow shall be as sharply bounded as possible, and for that purpose it is well to have the shadow cast by the edge rather than the flat side of the flame. The color of the yellowish shadow is objective and due to the yellow of the gas-flame, that of the blue is due to the contrast, but largely, as yet, to successive contrast. Put a dot in the centre of the blue shadow, to serve as a fixation-point, and another on the edge. Fasten a paper tube (preferably blackened inside) so that it can easily be shifted from one dot to the other. Cut off the gas-light by holding a card between it and the block; adjust the tube so that the dot in the middle of the shadow may be fixated without any of the field outside of the shadow being seen. Wait until all of the blue has disappeared from the shadow, and then, still looking through the tube, remove the card. The field remains entirely unchanged and appears, as before, a colorless gray. The former blue color is thus shown to be subjective and due to contrast with the yellow lighted area in which it lies.

---

[1] This setting of the experiment succeeds best when the daylight is weak, as, for example, just before the lights are usually lighted in the evening. If the experiment is to be made in broad day, the light must be reduced by curtains or otherwise; if at night, there must be two lights, one corresponding to the window and one to the gas, and the latter must shine through a pane of colored glass. If yellow glass is used, the colors will be the same as those in this experiment, the free flame taking the place of the daylight. If the sky is clear, its light is itself blue, and would complicate the experiment somewhat. Its light may, however, be passed through colored glass or gelatine, but then the orange color of the gas-light must be regarded.

b. Cut off the gas-light again and adjust the tube so that the dot in the edge of the shadow may be fixated. Taking great care not to move the eye, withdraw the card. The part of the field of the tube filled by the shadow will appear bluish, that of the remainder reddish yellow. After a little time of steady fixation, cut off the gas-light once more and observe the instant reversal of the colors. The shadow now appears in reddish yellow, the rest of the field blue. The color of the shadow, both before and after the final interposition of the card, is due to simultaneous contrast, in the first case with the reddish yellow light, and in the second with its after-image.

Helmholtz and his supporters explain all cases of simultaneous contrast as errors of judgment; in the case of the colored shadow, for example, we mistake the yellow of the gas-lighted field for white, and consequently find the shadow which is really gray to be bluish. In the case of this particular experiment, Hering and Delabarre have shown this psychological explanation unnecessary and a physiological one all sufficient, and Hering has done the same for other forms of experiments.

On simultaneous contrast in general, see Helmholtz, *A*, 542 ff., Fr. 515–547 (392–418); Hering, *A* and *E*. On colored shadows see Helmholtz, *A*, 551–553, Fr. 517–519 (394–396); Hering, *E*; Delabarre.

On Helmholtz's theory see Helmholtz, *A*, 543 ff., Fr. 516, 533–538 (392, 407–411); Hering, *E*; Rood, *A*, 252 ff.; von Bezold, *B*, 146 ff.

For quantitative measurements of simultaneous contrast under various conditions, see Kirschmann, *D*.

156. Simultaneous Contrast. Hering's Binocular Method.

a. Set a red glass in the right frame of the binocular color-mixer, a blue glass in the left. Look fixedly through the colored glasses at the cork ball below, bringing the eyes close to the glasses and the nose between them. Adjust the side screens till the white ground below appears in a uni-

form light violet from the binocular mixture of the red and blue (see Ex. 167). The narrow strip of black paper on the white is seen double, the right hand image bluish, the left yellowish.

b. The possibility of successive contrast, however, is not yet excluded. Lay a sheet of black paper over the whole of the white field and its black strip; rest the eyes; and finally, when everything is in readiness, and the eyes again fixed on the ball, swiftly draw away the black paper, keeping the eyes motionless. The contrast colors are seen on the instant, before any motions of the eyes that might introduce successive contrast have been made.

Hering argues that this experiment is conclusive against the psychological explanation of simultaneous contrast, unless a separate unconscious judgment is to be made for each eye; for that which is seen is a light violet field, and the contrast color to that should be a greenish yellow, and both images of the strip should be alike, whereas, actually, the images appear in different colors, neither of which is the color required.

Hering, *J.*

157. Induction of a Like Color. An effect the reverse of the ordinary contrast effects sometimes appears, the inducing color reappearing in the induced field.

a. Place close side by side a large piece of black paper and an equal sized piece of white. Make a dot as a fixation point at the middle of their line of junction, and stare fixedly at it for half a minute. After a few seconds the white will appear decidedly darker and the black decidedly lighter, the effect becoming more marked as fixation is continued. See also Ex. 122.

b. A darkening or brightening of a colored ground is often to be observed when a figure in black or white is placed

upon it. This is a method of obtaining shades and tints often used in polychromatic decoration. Observe the effect in Fig. 4 of Plate I. The same may be observed occasionally in plaid fabrics, and is shown very satisfactorily in kindergarten mats woven in checker-board pattern of colored and gray papers. If a set of graded grays is used so that the strips may range evenly from a black at one side to a white at the other, the corresponding shading of the colored paper is striking.

On *a*, Helmholtz, *A*, 554 ff., Fr. 527 ff. (401 ff.); Hering, *A*, 36 ff. On *b*, von Bezold, *B*, 182–183 and Plate V. For what is perhaps a related phenomenon, see Brücke, 424 ff.; Helmholtz, *A*, 549, Fr. 520 (396); Aubert, *A*, 549 f.

158. Influence of Experience in Visual Perception. While in the previous experiments a physiological explanation seems sufficient for the facts, psychical action is not excluded, even by Hering, from a considerable share in sense perception. In the following experiments experience cooperates in the result.

a. Place upon the color-mixer a short-pointed star of white cardboard, or even a square; when in sufficiently rapid rotation, it appears as a white central circle surrounded by a more or less transparent ring. While in this condition bring behind it a broad strip of black cardboard of somewhat greater length than the diameter of the star from point to point. As the edge of the card advances, it can be seen not only behind the transparent ring, but, apparently, also behind the opaque central circle, and the portions of the latter in front of the black card seem darkened by its presence. The illusion holds, though with a lightening instead of a darkening effect, when a white card is moved behind a black star. The illusion fails by degrees if the card is kept motionless, but may be observed to a certain extent when the star is at rest, or even on a square of card-

board held in the hand while another is moved to and fro behind it. In all cases the latter card should often be wholly withdrawn, so that its edge can be clearly seen.

b. Cover a piece of black cardboard smoothly with tissue paper, and notice that it seems at first blacker (because its color is well known) than it afterwards proves to be on comparison with other grays.

c. In mixing colors by reflection (Ex. 150 *a*), notice the tendency to see one color through the other, instead of seeing the mixture of the two. This tendency may be so strong at first as to interfere, to a certain extent, with the success of the experiment. See also Ex. 164.

Helmholtz, *A*, 312, 323 f., Fr. 360 (273); Kirschmann, *E*. On the difficulty of judging small differences in the color of surfaces that present other small unlikenesses, see Hering, *E*.

Some Phenomena of Rotating Disks.

159. The Münsterberg-Jastrow Phenomenon. *a.* Set a black and white disk, e.g., that used in Ex. 145 *a*, in rapid enough rotation to give a uniform gray; pass rapidly before it a thin wooden rod or thick wire, and notice the multitude of shadowy images of the rod that appear on the disk. The number of images is greatest in the portion of the disk having the most frequent interchange of black and white.

b. Replace the disk by one carrying two or more colors. Notice the repetition of the phenomenon, and that the colors of the images are the colors (otherwise completely blended) which the disk actually carries. The explanation of the phenomenon is not altogether clear, but the sudden changes of the background against which the rod is seen seem to have an effect not unlike that of a stroboscopic disk or of intermittent illumination, and thus show the rod at rest in its successive positions.

Jastrow.

160. Retinal Oscillation. Prepare a disk of black cardboard 25–30 cm. in diameter, and paste upon it a sector of white of 90° extent. Put the disk in slow rotation (one turn a second), fixate the middle of the disk, and notice that the retreating edge of the black is always followed by a narrow shadowy sector in the white. Under favorable conditions more than one may be seen. The retina on first being stimulated with white, apparently reacts in the direction of black (see Ex. 125), then swings again toward white, and so on.

Charpentier, *B*.

161. Perception of Flicker with Different Parts of the Retina. Place upon the color-mixer a black and white disk in which the sectors are complete from centre to circumference; those used in Ex. 145 will not answer here. Rotate the disk at such a rate as to give a lively flicker, fixate its centre and slowly increase the rate. With care a point will be found where the sectors are blended for the central parts of the retina, but still flicker for the periphery. Try also looking at one edge of the disk while giving attention to the centre or opposite edge. This is in accord with the general principle that peripheral after-images are of shorter duration than those of the retinal centre. Too bright illumination should be avoided, for with intense light the difference between the centre and periphery is less, or even quite reversed.

Bellarminow. On rotating disks and their phenomena in general, see Helmholtz, *A*, 480–501, Fr. 445–471 (337–357).

BINOCULAR PHENOMENA OF LIGHT AND COLOR.[1]

162. In general the two eyes co-operate to bring about a single visual result, but the union of the impressions upon the two retinæ is influenced by a number of circumstances.

[1] The experiments that follow can all be made with the stereoscope, but practice will enable the experimenter to combine the diagrams with free eyes, either by crossing the lines of sight (fixating a point nearer than the diagram), or by making them parallel or nearly so (fixating a point beyond the diagram). This

a. If the stimulus to one eye is considerably stronger than that to the other, the sensation in the latter is in most cases totally suppressed. Close one eye and look at a sheet of white paper with the other, letting the open eye move about freely. There is no tendency for the darkened field of the closed eye to assert itself.

b. When, however, the effect of the stimulus in the open eye is somewhat weakened by steady fixation, such a tendency is to be observed, and the whole of the field of the open eye, except a small area about the point fixated, may be suppressed from time to time by the dark field of the closed eye. A slight motion will, however, instantly restore the first. See also Ex. 127.

c. A field that contains sharply marked objects or contours will generally triumph over one that does not. Try combining the letters below in such a way that the B's are superposed. In this diagram the white field of either eye, which corresponds to A or C in the other eye, will generally not triumph over the letter.

AB BC

Helmholtz, *A*, Fr. 964 ff. (767 ff.); Hering, *P*, 380–385; Aubert, *A*, 550–553; Wundt, *A*, 3te Aufl., II., 183 ff., 4te Aufl., II., 209 ff.

163. Fechner's Paradoxical Experiment. Hold close before one eye a dark glass, such as is used in protecting the eyes, or a piece of ordinary glass moderately smoked over, or even a black card with a good-sized pin-hole in it, allowing the other eye to remain free. It is easy to see that the

skill the experimenter should try to acquire. In these experiments it is important that the eyes should be of approximately equal power; and if the poorer eye cannot be helped with lenses, the vision of the other must be somewhat reduced by the interposition of a sufficient number of plates of ordinary glass.

binocular field is darkened by the interposition of the dark glass. If, however, the eye behind the glass is closed, or the light wholly cut off from it by holding a black card in front of the glass, the field appears decidedly brighter; that is to say, cutting off a portion of the stimulus received by the total visual apparatus, has caused an increased intensity of sensation. The experiment fails for very dark and very light glasses. Several explanations have been given, but that of Aubert (according to which the sensations of the two retinæ blend in a sort of average result when the difference is not too great, but one wholly suppresses the other when the difference is very great) seems to be the most satisfactory.

Fechner, *B*, 416 ff.; Helmholtz, *A*, Fr. 993-994 (790-791); Hering, *Q*, 311 f.; Aubert, *A*, 499-503.

164. Rivalry. When the two retinæ are stimulated at the same time separately with strong light of different colors, or are confronted with otherwise incongruous fields, i.e., fields that cannot be given a unitary interpretation, there results a peculiar instability and irregular alternation of the colors over part or the whole of the combined fields of vision. This apparent struggle of the fields is known as Retinal Rivalry. Hold close before one eye a piece of blue glass, before the other a piece of red glass, and look toward the sky or a brightly lighted uniform wall. The struggle of colors will at once begin. The same may be observed with a stereoscope when the usual paired photographs are replaced by colored fields, or even with no apparatus at all, when both eyes are closed and turned toward a bright sky and one of them is covered with the hand. Long looking generally tends to quiet the rivalry. Rivalry has been explained as due to fluctuations of attention, and some observers find that it can be more or less controlled by attention (Helmholtz). Fechner discusses the attention

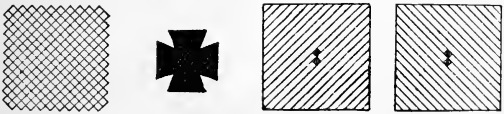
theory, and finds it insufficient. Von Bezold thinks rivalry associated with changes in accommodation which follow attention. Hering and others regard the changes as of more purely physiological origin. See also Ex. 165 *b*.

Helmholtz, *A*, Fr. 964 ff. (767 ff.), 974 ff. (775 ff.); Hering, *P*, 380–385, *Q*, 308 ff.; Aubert, *A*, 550 ff.; Wundt, *A*, 3te Aufl., II., 185 ff., 4te Aufl., II., 211 ff.; Chauveau, *C*.

165. Prevalence and Rivalry of Contours. By contours is here meant lines of separation where fields of one color border upon fields of another color.

a. Combine stereoscopically the two bars below, and notice that it is the contours that suppress the solid parts of both the black and white. This figure gives excellent results also when colors are substituted for the black and white.

Notice a similar triumph of the contours of the cross in the left-hand figure below, or, better still, in an enlargement of it.



b. Notice the rivalry of the contours in all of these figures.

c. The last two pairs of diagrams are suitable for the study of the part played by attention in rivalry. While it is doubtful whether mere attention to one field or the other can cause it to predominate, it yet seems possible by indirect application of attention to cause it to do so. If attention is given to an *examination* of the lines and small squares in the left-hand figure, or if one of the sets of lines in the right-hand figure is counted, both will appear to be somewhat assisted in their struggle with the cross or the other set of lines.

d. A printed page has a decided advantage. Try a diagram in which a printed page is put in rivalry with a field of heavy cross lines. The lines will be found to yield to the print, at least at the point at which the reader is looking at the instant. Two printed pages, however, become hopelessly mixed; and it is hard to say how much of the advantage, when a single one is used, is due to its superior power as a holder of attention, and how much to its excellence as a set of contours. A portion of the power of contours is probably to be explained by the mutual intensification of both the black and the white by contrast; but a part is perhaps due to a strong tendency, observable in other cases also, for the eyes (and attention) to follow lines, and especially outlines.

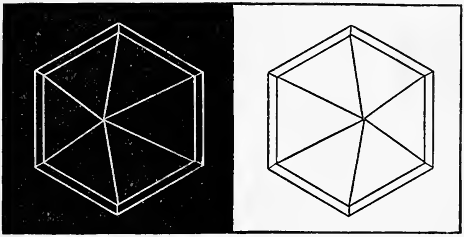
Helmholtz, *A*, Fr. 964 ff. (767 ff.); Hering, *P*, 380–385, *Q*, 314; Wundt, *A*, 3te Aufl., II., 183 ff., 4te Aufl., II., 209 ff.

166. Luster. & Sheen. When one of the rival fields is white and the other colored (especially when one is white and the other is black), there results, besides the rivalry, a curious illusion of shine or polish, known as binocular lustre.

a. Examine in the stereoscope a diagram made like the accompanying cut, and notice the graphite-like shine of the

MADE IN U.S.A.

pyramid. The explanation seems to be that polished surfaces, which at some angles reflect light enough to look



white, and at others appear in their true color, have often in previous experience given rise to such differences of sensation in the two eyes, and from this difference it is inferred that the object seen in the diagram is shiny.

b. A species of monocular lustre (or transparence) is to be observed when black or white or colors are combined by means of the reflection color-mixer, especially when the inclination of the plate is so changed that one color appears to be reflected in the surface of the other, or to be seen through and behind it. The experiment works well when real objects are reflected in the surface of the glass, the reflecting power of the latter appearing to be transferred to the horizontal surface on the opposite side.

Helmholtz, *A*, Fr. 983 ff. (782 ff.); Hering, *P*, 576–577; Aubert, *A*, 550 ff.; Wundt, *A*, 3te Aufl., II., 177 ff., 183 ff., 4te Aufl., II., 204 ff., 209 ff.

167. Binocular Color Mixing. The result of simultaneous presentation of different colors to the two eyes is not always rivalry or lustre. If the colors are not too bright and saturated, and the fields are without fleck or spot to

give one the predominance, a veritable, though somewhat unsteady, mixture of the colors may result.

a. Place a red and a blue glass of equal transparency in the binocular color-mixer, and adjust the side screens till the proper amount of white light is mixed in with that transmitted from below. The mixture will then be seen on the white field below. Try also with other combinations of glasses. Mixtures obtained in this way are not always the same in appearance as the monocular mixtures studied above, and some observers have great difficulty in getting them satisfactorily. Long and steady gazing, which interferes with rivalry, favors binocular color mixing.

b. The same effect may be conveniently obtained with a stereoscope, from which the middle partition has been removed. Try with equal areas of dull colors of little saturation. Hering recommends two squares of red and two of blue, set at equal distances in a horizontal line, the two reds on one side, the two blues on the other. When the middle pair are combined stereoscopically, they show a mixed color, while the unmixed colors can be seen for comparison beside them. He also suggests the use of lenses to prevent sharp focusing of the eyes upon the contours, which interferes with the mixture. Complementary colors are said to be more difficult to fuse than those standing nearer in the color scale. The same is true of colors differing greatly in brightness; see Ex. 163.

Helmholtz, *A*, Fr. 976 ff. (776 ff.); Hering, *P*, 591–600; von Bezold, *C*; Chauveau, *A*; Aubert, *A*, 550 ff.; Wundt, *A*, 3te Aufl., II., 183 ff., 4te Aufl., 209 ff.

168. Binocular Contrast. The Side-Window Experiment. Stand so that the light from the window falls sidewise into one eye, but not at all into the other. Place in a convenient position for observation a strip of white paper on a black surface. The paper when looked at with both eyes appears

perfectly colorless. On looking now at a point nearer than the strip of paper (e.g., at the finger held up before the face), double images of the strip will be seen. The two images will be different in brightness and slightly tinged with complementary colors. The image belonging to the eye next the window (which may be recognized by its disappearance when that eye is closed) will appear tinged with a faint blue or blue-green color, the other with a very faint red or yellow. The light that enters the eye through the sclerotic is tinged reddish yellow, and makes the eye less responsive to that color; the white of the paper strip therefore appears bluish. It appears darker partly for a similar reason, and perhaps also, as Fechner suggests, because it lies in a field which, for the eye in question, is generally bright. The reddish color of the other eye's image of the strip is explained as due to contrast with the first, but whether this contrast color is a psychical matter, or whether it is to be explained by the action of the stimulus in the first eye upon the second, as there seems some reason to think, is as yet uncertain. Its greater brightness is probably due to the fresher condition of the eye to which it belongs, and to contrast with its less brilliant field. The same thing is often to be noticed when reading with the lamp at one side, or even when one eye has been closed for a short time while the other has been open. The double images are in no wise essential; simple alternate winking will show decided differences in the condition of the two eyes.

Fechner, *B*, 511 ff.; Brücke, 420 ff.; Hering, *P*, 600–601; Helmholtz, *A*, Fr. 987 ff. (785 ff.); Chauveau, *B*; Titchener; Wundt, *A*, 3te Aufl., II., 183 ff., 4te Aufl., II., 209 ff.

169. Binocular After-Images. Lay a bit of orange-colored paper on a dark ground, and provide two white cards. Hold one of the cards close to the left eye, but a little to one side, so as not to hide the bit of paper. Hold the other

eight or ten inches from the right eye in such a way as to hide the paper. Look at the paper for a few seconds with the left eye, then bring the card before it. A faint, washy, orange-colored positive after-image will appear on the card before the right eye. The image is by no means easy to observe. It is supposed to belong to the right eye's half of the visual apparatus, possibly to the central, i.e., cerebral, part.

Ebbinghaus, *C*; Chauveau, *B*; Titchener.

BIBLIOGRAPHY.

ABNEY: *A*. On the Examination for Colour of Cases of Tobacco Scotoma and of Abnormal Colour Blindness, *Proc. Roy. Soc.*, XLIX., 1891, 491-508.

B. On the Limit of Visibility of the different Rays of the Spectrum, *ibid.*, XLIX., 1891, 509-518.

C. The Sensitiveness of the Eye to Light and Colour. *Nature*, XLVII., 1892-93, 538-542.

ABNEY AND FESTING: Colour Photometry, iii., *Phil. Trans.*, CLXXXIII., 1892, A, 531-565.

ALBERT: Ueber die Aenderung des Farbentones von Spectralfarben und Pigmenten bei abnehmen der Lichtstärke, *Wiedemann's Annalen*, XVI., 1882, 129-160.

AUBERT: *A* and *B*. Works cited with same letters in bibliography of Chap. V.

BELLARMINOW: Ueber intermittirende Netzhautreizung, *von Graefe's Archiv*, XXXV., 1889, i., 25-49.

BENSON: Manual of the Science of Colour, London, 1871.

VON BEZOLD: *A*. Ueber das Gesetz der Farbenmischung und die physiologischen Grundfarben, *Poggendorff's Annalen*, CL., 1873, 71-93, 221-247.

B. The Theory of Color in its Relation to Art and Art Industry, Boston, 1876.

C. Ueber binoculare Farbenmischung, *Poggendorff's Annalen*, Jubelband [1874], 585–590. Cites earlier literature.

BRODHUN: *A.* Ueber die Empfindlichkeit des grünblinden und des normalen Auges gegen Farbenänderung im Spektrum, *Zeitschrift für Psychologie*, III., 1892, 97–107.

B. Die Gültigkeit des Newton'schen Farbenmischungsgesetzes bei dem sog. grünblinden Farbensystem, *ibid.*, V., 1893, 323–334. Cites literature.

BRUCKE: Untersuchungen über subjective Farben, *Poggendorff's Annalen*, LXXXIV., 1851, 418–447.

CHARPENTIER: *A* and *B.* Work cited with same letters in bibliography of Chap. V.

C. Sur le retard dans la perception des divers rayons spectraux, *Comptes rendus*, CXIV., 1892, 1423–1426.

CHAUVEAU: *A.* Sur la fusion des sensations chromatiques perçues isolément par chacun des deux yeux, *Comptes rendus*, CXIII., 1891, 358–362.

B. Sur les sensations chromatiques exercitées dans l'un des deux yeux par la lumière colorée qui éclaire la rétine de l'autre œil, *ibid.*, 394–398.

C. Sur la théorie de l'antagonisme des champs visuels, *ibid.*, 439–442.

CHEVREUL: The Principles of Harmony and Contrast of Colours, London, 1859.

DELABARRE: Colored Shadows, *American Journal of Psychology*, II., 1888–89, 636–643.

DONDERS: *A.* Ueber Farbensysteme, *von Graefe's Archiv*, XXVII., 1881, i., 155–223.

B. Noch einmal die Farbensysteme, *ibid.*, XXX., 1884, i., 15–90.

C. Farbengleichungen, *DuBois-Reymond's Archiv*, 1884, 518–552.

DOVE: Versuche über subjective Complementarfarben, *Poggendorff's Annalen*, XLV., 1838, 158–162.

EBBINGHAUS: *A.* Theorie des Farbensehens, *Zeitschrift für Psychologie*, V., 1893, 145–238. Full statement of matter presented in outline before the Psychological Congress in London, 1892, Proceedings, 101–103.

B. Die Gesetzmässigkeit des Helligkeitscontrastes, *Sitz.-ber. der Akademie zu Berlin*, 1., Dec., 1887.

C. Ueber Nachbilder im binocularen Sehen und die binocularen Farbenerscheinungen überhaupt, *Pflüger's Archiv*, XLVI., 1890, 498–508.

EBERT: Ueber den Einfluss der Schwellenwerthe der Lichtempfindung auf den Charakter der Spectra, *Wiedemann's Annalen*, XXXIII., 1888, 136–155.

EXNER: *A.* Bemerkungen über intermittirende Netzhautreizung, *Pflüger's Archiv*, III., 1870, 214–240.

B. Ueber eine neue Urtheilstäuschung im Gebiete des Gesichtssinnes, *ibid.*, XXXVII., 1885, 520–522, (this part also in *Biol. Centralbl.*, VI.) ; XL., 1887, 323–330.

FECHNER: *A.* Ueber eine Scheibe zur Erzeugung subjectiver Farben, *Poggendorff's Annalen*, XLV., 1838, 227-232.

B. Ueber einige Verhältnisse des Binocularen Sehens, *Abhl. d. k. sächs. Ges. d. Wiss.*, VII., 1860, 339-564.

FICK, A.: *A.* Zur Theorie des Farbensinnes bei indirektem Sehen, *Pflüger's Archiv*, XLVII., 1890, 274–285.

B. Work cited with same letter in Chap. V.

FICK, A. E.: *A.* Eine Notiz über Farbenempfindung, *Pflüger's Archiv*, XVII., 1878, 152–153.

B. Studien über Licht- und Farbenempfindung, *ibid.*, XLIII., 1888, 441–501.

FRANKLIN, Christine Ladd: *A.* Eine neue Theorie der Lichtempfindung, *Zeitschrift für Psychologie*, IV., 1892, 211–221. Abstracts of this paper may be found in Proc. Congr. Exper. Psy., London, 1892; Johns Hopkins University Circulars, XII., No. 106, June, 1893, 108–110; Science, XXII., July 14, 1893, 18–19.

B. On Theories of Light Sensation, *Mind*, Ser. 2, II., 1893, 473–489.

HELMHOLTZ: *A.* Work cited with same letter in bibliography of Chap. V.

B. Popular Scientific Lectures, First Series, New York, 1885.

C. Versuch einer erweiterten Anwendung des Fechnerschen Gesetzes im Farbensystem, *Zeitschrift für Psychologie*, II., 1892, 1–30.

D. Versuch das psychophysische Gesetz auf die Farbenunterschiede trichromatischer Augen anzuwenden, *ibid.*, III., 1891, 1–20.

E. Kürzeste Linien im Farbensystem, *ibid.*, 108–122. An extract from *Sitz.-ber. der Akademie zu Berlin*, 17, December, 1891.

HERING:[1] *A.* Zur Lehre vom Lichtsinne, Wien, 1878. Reprint of six communications to the Vienna Academy, 1872–74. For an extended abstract of this work, made by Dr. William Pole, see *Nature*, XX., 1879, 611–613, 637–639; XXI., 1879–80, 14–17.

B. Zur Erklärung der Farbenblindheit aus der Theorie der Gegenfarben, Prag, 1880. Reprint from *Lotos*, Neue Folge, I., 1880.

C. Ueber individuelle Verschiedenheiten des Farbensinns, *Lotos*, Neue Folge, VI., 1885.

D. Beleuchtung eines Angriffes auf die Theorie der Gegenfarben, *Pflüger's Archiv*, XLI., 1887, 29–46.

E. Ueber die Theorie des simultanen Contrastes von Helmholtz, *ibid.*, XL., 1886–87, 172–191 (Die farbigen Schatten); XLI., 1887, 1–29 (Der Contrastversuch von H. Meyer und die Versuche am Farbenkreisel); 358–367 (Der Spiegelcontrastversuch); XLIII., 1888, 1–21 (Die subjective „Trennung des Lichtes in zwei complementäre Portionen").

F. Ueber die von v. Kries wider die Theorie der Gegenfarben erhobenen Einwände, *ibid.*, XLII., 1888, 488–506; XLIII., 1888, 264–288, 329–346.

G. Ueber die Hypothesen zur Erklärung der peripheren Farbenblindheit, *v. Graefe's Archiv*, XXXV., 1889, iv., 63–83; XXXVI., 1890, i., 264.

H. Zur Diagnostik der Farbenblindheit, *ibid.*, XXXVI., 1890, i., 217–233.

I. Die Untersuchung einseitiger Störungen des Farbensinnes mittels binocularer Farbengleichungen, *ibid.*, XXXVI., 1890, iii., 1–23.

J. Beitrag zur Lehre vom Simultankontrast, *Zeitschrift für Psychologie*, I., 1890, 18–28.

---

[1] Hering's work upon color has not yet been gathered into one consecutive whole. It has seemed well, therefore, to insert here, in addition to the titles of papers bearing directly on the experiments of Chap. VI., such other titles on light and color as came to hand.

K. Eine Methode zur Beobachtung des Simultancontrastes, *Pflüger's Archiv*, XLVII., 1890, 236–242.

L. Prüfung der sogenannten Farbendreiecke mit Hülfe des Farbensinns excentrischer Netzhautstellen, *ibid.*, XLVII., 1890, 417–438.

M. Ueber Newton's Gesetz der Farbenmischung, Prag, 1887. Reprint from *Lotos*, VII., 1887.

N. Untersuchung eines total Farbenblinden, *Pflüger's Archiv*, XLIX., 1891, 563–608.

O. Eine Vorrichtung zur Farbenmischung, zur Diagnose der Farbenblindheit und zur Untersuchung der Contrasterscheinungen, *Pflüger's Archiv*, XLII., 1888, 119–144.

P. Work cited with reference letter *A* in the bibliography of Chap. V.

Q. Work cited with reference letter *B* in the bibliography of Chap. V.

R. Ueber Holmgren's vermeintlichen Nachweis der Elementarempfindungen des Gesichtssinns, *Pflüger's Archiv*, XL., 1887, 1–20.

S. Kritik einer Abhandlung von Donders, *Lotos*, Neue Folge, II., Prag, 1882.

T. Ueber Sigmund Exner's neue Urtheilstäuschung auf dem Gebiete des Gesichtsinnes, *Pflüger's Archiv*, XXXIX., 1886, 159–170.

U. Ueber den Begriff „Urtheilstäuschung" in der physiologischen Optik und über die Wahrnehmung simultaner und successiver Helligkeitsunterschiede, *ibid.*, XLI., 1887, 91–106.

Hess: *A.* Ueber den Farbensinn bei indirectem Sehen, *v. Graefe's Archiv*, XXXV., 1889, iv., 1–62.

B. Untersuchung eines Falles von halbseitiger Farbensinnsstörung am linken Auge, *ibid.*, XXXVI., 1890, iii., 24–36.

C. Ueber die Tonänderungen der Spektralfarben durch Ermüdung der Netzhaut mit homogenem Lichte, *ibid.*, XXXVI., 1890, i., 1–32.

Hillebrand: Work cited in bibliography of Chap. V.

Holmgren: Color-blindness in its Relation to Accidents by Rail and Sea. Translation by M. L. Duncan, *Smithsonian Report*, 1877, 131–195.

JASTROW: A Novel Optical Illusion, *American Journal of Psychology*, IV., 1891–92, 201–208.

JEFFRIES: *A.* Color-blindness, its Dangers and its Detection, Boston, 1879. This work contains a seventeen-page bibliography on color-blindness and kindred topics.

B. Color-blindness, Article in the Reference Handbook of the Medical Sciences, New York, 1886, II., 241.

KIRSCHMANN: *A.* Beiträge zur Kenntniss der Farbenblindheit, *Wundt's Philos. Studien*, VIII., 1892–93, 173–230, 407–430.

B. Ueber die Helligkeitsempfindung im indirecten Sehen, *ibid.*, V., 1889, 447–497.

C. Die Farbenempfindung im indirecten Sehen, Erste Mittheilung, *ibid.*, VIII., 1892–93, 592–614.

D. Ueber die quantitativen Verhältnisse des simultanen Helligkeits- und Farben-Contrastes, *ibid.*, VI., 1890, 417–491.

E. Some Effects of Contrast, *American Journal of Psychology*, IV., 1892, 542–557.

KÖNIG: *A.* Ueber den Helligkeitswert der Spektralfarben bei verschiedener absoluter Intensität, Beiträge zur Psychologie und Physiologie der Sinnesorgane (Helmholtz Festgruss), Hamburg und Leipzig, 1891, 311–388.

B. The Modern Development of Thomas Young's Theory of Colour Vision, *Report of British Association, Birmingham Meeting*, 1886, 431–439.

C. Zur Kenntniss dichromatischer Farbensysteme, *Wiedemann's Annalen*, XXII., 1884, 567–578.

KÖNIG UND DIETERICI: *A.* Die Grundempfindungen in normalen und anomalen Farbensystemen und ihre Intensitätsverteilung im Spektrum, *Zeitschrift für Psychologie*, IV., 1892, 241–347.

B. Ueber die Empfindlichkeit des normalen Auges für Wellenlängenunterschiede des Lichtes, *Wiedemann's Annalen*, XXII., 1884, 579–589.

VON KRIES: Die Gesichtsempfindungen und ihre Analyse, *Du Bois-Reymond's Archiv*, 1882, Supplement-Band, 1–178. A careful summary and discussion of the whole subject.

LEHMANN: Ueber die Anwendung der Methode der mittleren Abstufungen auf den Lichtsinn; die quantitative Bestimmung des Lichtcontrastes, *Wundt's Philos. Studien*, III., 1886, 516–528.

MAXWELL: *A.* On the Theory of Compound Colours, and the Relation of the Colours of the Spectrum, *Phil. Trans.*, CL., 1860, 57–84.

B. On Colour Vision, *Proc. Royal Institution of Great Britain*, VI. These two papers are also to be found in Maxwell's Scientific Papers, Cambridge, 1890, I., 410–440, II., 267–280.

MAYER: Studies of the phenomena of Simultaneous Contrast-Color; and on a Photometer for measuring the intensities of Lights of different colors, *American Journal of Science*, Ser. 3, XLVI., 1893, 1–22; also *Phil. Mag.*, Ser. 5, XXXVI., 1893, 153–175.

MEYER: Ueber Contrast- oder Complementarfarben, *Poggendorff's Annalen*, XCV., 1855, 170–171; also *Phil. Mag.*, Ser. 4, IX., Jan.–June, 1855, 547.

NICHOLS: *A.* On the Sensitiveness of the Eye to Colors of a Low Degree of Saturation, *American Journal of Science*, Ser. 3, XXX., 1885, 37–41.

B. Duration of Color Impressions upon the Retina, *American Journal of Science*, Ser. 3, XXVIII., 1884, 243–252.

PACE: Zur Frage der Schwankungen der Aufmerksamkeit nach Versuchen mit der Masson'schen Scheibe, *Wundt's Philos. Studien*, VIII., 1892–93, 388–402.

PEIRCE, B. O., JR.: On the Sensitiveness of the Eye to Slight Differences of Color, *American Journal of Science*, Ser. 3, XXVI., 1883, 299–302.

PEIRCE, C. S.: Note on the Sensation of Color, *American Journal of Science*, Ser. 3, XIII., 1877, 247–251.

PLATEAU: Betrachtungen über ein von Hrn. Talbot vorgeschlagenes photometrisches Princip, *Poggendorff's Annalen*, XXXV., 1835, 457–468.

POLE: Further Data on Colour-Blindness, *Phil. Mag.*, Ser. 5, XXXIV., 1892, 100–114, 439–443, XXXV., 1893, 52–62, XXXVI., 1893, 188–195.

PREYER: Work cited in bibliography of Chap. I.

RAYLEIGH: *A.* Experiments on Colour, *Nature*, XXV., 1881–82, 64–66.

B. Rayleigh and others: Report of the [Royal Society's] Committee on Colour-Vision, *Proc. Roy. Soc.*, LI., No. 311, July 19, 1892, 281–396.

ROOD: *A*. Students' Textbook of Color, New York, 1881.

B. On a new Theory of Light, proposed by John Smith, M.A., *American Journal of Science*, Ser. 2, XXX., 1860, 182–186.

SCHUSTER: Experiments with Lord Rayleigh's Colour Box, *Proc. Roy. Soc.*, XLVIII., 1890, 140–149.

TALBOT: Experiments on Light, *Phil. Mag.*, Ser. 3, V., July–Dec., 1834, 321–334, especially, 327–334.

TITCHENER: Ueber binoculare Wirkungen monocularer Reize, *Wundt's Philos. Studien*, VIII., 1892–93, 231–310. Cites literature.

WUNDT: *A*. Work cited with same letter in the bibliography of Chap. V.

B. Die Empfindung des Lichts und der Farben, *Wundt's Philos. Studien*, IV., 1888, 311–389.

For further bibliographical references, see the works of Helmholtz and Aubert and the following by Plateau: Bibliographie analytique des principaux phénomènes subjectifs de la vision, depuis les temps anciens jusqu'à la fin du XVIII. siècle; suivie d'une bibliographie simple pour la partie écoulée du siècle actuel. Mém. cour. de l'Acad. R. de Belgique; Bruxelles, 1876–77.

ENGLISH LITERATURE.

Hawthorne and Lemmon's American Literature. A manual for high schools and academies. $1.25.

Meiklejohn's History of English Language and Literature. For high schools and colleges. A compact and reliable statement of the essentials; also included in Meiklejohn's English Language (see under English Language). 90 cts.

Meiklejohn's History of English Literature. 116 pages. Part IV of English Literature, above. 45 cts.

Hodgkins' Studies in English Literature. Gives full lists of aids for laboratory method. Scott, Lamb, Wordsworth, Coleridge, Byron, Shelley, Keats, Macaulay, Dickens, Thackeray, Robert Browning, Mrs. Browning, Carlyle, George Eliot, Tennyson, Rossetti, Arnold, Ruskin, Irving, Bryant, Hawthorne, Longfellow, Emerson, Whittier, Holmes, and Lowell. A separate pamphlet on each author. Price 5 cts. each, or per hundred, $3.00; complete in cloth (adjustable file cover, $1.50). $1.00.

Scudder's Shelley's Prometheus Unbound. With introduction and copious notes. 70 cts.

George's Wordsworth's Prelude. Annotated for high school and college. Never before published alone. $1.25.

George's Selections from Wordsworth. 168 poems chosen with a view to illustrate the growth of the poet's mind and art. $1.50.

George's Wordsworth's Prefaces and Essays on Poetry. Contains the best of Wordsworth's prose. 60 cts.

George's Webster's Speeches. Nine select speeches with notes. $1.50.

George's Burke's American Orations. Cloth. 65 cts.

George's Syllabus of English Literature and History. Shows in parallel columns, the progress of History and Literature. 20 cts.

Corson's Introduction to Browning. A guide to the study of Browning's Poetry. Also has 33 poems with notes. $1.50.

Corson's Introduction to the Study of Shakespeare. A critical study of Shakespeare's art, with examination questions. $1.50.

Corson's Introduction to the Study of Milton. *In press.*

Corson's Introduction to the Study of Chaucer. *In press.*

Cook's Judith. The Old English epic poem, with introduction, translation, glossary and fac-simile page. $1.60. Students' edition without translation. 35 cts.

Cook's The Bible and English Prose Style. Approaches the study of the Bible from the literary side. 60 cts.

Simonds' Sir Thomas Wyatt and his Poems. 168 pages. With biography, and critical analysis of his poems. 75 cts.

Hall's Beowulf. A metrical translation. $1.00. Students' edition. 35 cts.

Norton's Heart of Oak Books. A series of five volumes giving selections from the choicest English literature.

Phillips's History and Literature in Grammar Grades. An essay showing the intimate relation of the two subjects. 15 cts.

See also our list of books for the study of the English Language.

D. C. HEATH & CO., PUBLISHERS.

BOSTON. NEW YORK. CHICAGO.

READING.

Badlam's Suggestive Lessons in Language and Reading. A manual for primary teachers. Plain and practical; being a transcript of work actually done in the school-room. $1.50.

Badlam's Stepping-Stones to Reading.— A Primer. Supplements the 283-page book above. Boards. 30 cts.

Badlam's First Reader. New and valuable word-building exercises, designed to follow the above. Boards. 35 cts.

Bass's Nature Stories for Young Readers: Plant Life. Intended to supplement the first and second reading-books. Boards. 30 cts.

Bass's Nature Stories for Young Readers: Animal Life. Gives lessons on animals and their habits. To follow second reader. Boards. 40 cts.

Fuller's Illustrated Primer. Presents the word-method in a very attractive form to the youngest readers. Boards. 30 cts.

Fuller's Charts. Three charts for exercises in the elementary sounds, and for combining them to form syllables and words. The set for $1.25. Mounted, $2.25.

Hall's How to Teach Reading. Treats the important question: what children should and should not read. Paper. 25 cts.

Miller's My Saturday Bird Class. Designed for use as a supplementary reader in lower grades or as a text-book of elementary ornithology. Boards. 30 cts.

Norton's Heart of Oak Books. This series is of material from the standard imaginative literature of the English language. It draws freely upon the treasury of favorite stories, poems, and songs with which every child should become familiar, and which have done most to stimulate the fancy and direct the sentiment of the best men and women of the English-speaking race. Book I, 100 pages, 25 cts.; Book II, 142 pages, 35 cts.; Book III, 265 pages, 45 cts.; Book IV, 303 pages, 55 cts.; Book V, 359 pages, 65 cts.; Book VI, 367 pages, 75 cts.

Smith's Reading and Speaking. Familiar Talks to those who would speak well in public. 70 cts.

Spear's Leaves and Flowers. Designed for supplementary reading in lower grades or as a text-book of elementary botany. Boards. 30 cts.

Ventura's Mantegazza's Testa. A book to help boys toward a complete self-development. $1.00.

Wright's Nature Reader, No. I. Describes crabs, wasps, spiders, bees, and some univalve mollusks. Boards. 30 cts.

Wright's Nature Reader, No. II. Describes ants, flies, earth-worms, beetles, barnacles and star-fish. Boards. 40 cts.

Wright's Nature Reader, No. III. Has lessons in plant-life, grasshoppers, butterflies, and birds. Boards. 60 cts.

Wright's Nature Reader, No. IV. Has lessons in geology, astronomy, world-life, etc. Boards. 70 cts.

For advanced supplementary reading see our list of books in English Literature.

D. C. HEATH & CO., PUBLISHERS,

BOSTON. NEW YORK. CHICAGO.

NUMBER.

White's Two Years with Numbers. Number Lessons for second and third year pupils. 40 cts.

Atwood's Complete Graded Arithmetic. Present a carefully graded course in arithmetic, to begin with the fourth year and continue through the eighth year. Part I. 200 pages. Cloth. 40 cts. Part II. 382 pages. Half leather. 75 cts.

Walsh's Mathematics for Common Schools. Special features of this work are its division into half-yearly chapters instead of the arrangement by topics; the omission, as far as possible, of rules and definitions; the great number and variety of the problems; the use of the equation in solution of arithmetical problems; and the introduction of the elements of algebra and geometry. Part I. 218 pages. 35 cts. Part. II. 252 pages. 40 cts. Part III. 365 pages. Half leather. 75 cts.

Sutton and Kimbrough's Pupils' Series of Arithmethics.

PRIMARY BOOK. Embraces the four fundamental operations in all their simple relations. 80 pages. Boards. 22 cts.

INTERMEDIATE BOOK. Embraces practical work through the four operations cancellation, factoring and properties of numbers, simple and decimal fractions, percentage and simple interest. 128 pages. Boards. 25 cts.

LOWER BOOK. Combines in one volume the Primary and Intermediate Books. 208 pages. Boards, 30 cts. Cloth, 45 cts.

HIGHER BOOK. A compact volume for efficient work which makes clear all necessary theory. 275 pages. Half leather. 70 cts.

Safford's Mathematical Teaching. Presents the best methods of teaching, from primary arithmetic to the calculus. Paper. 25 cts.

Badlam's Aids to Number. *For Teachers. First Series.* Consists of 25 cards for sight-work with objects from one to ten. 40 cts.

Badlam's Aids to Number. *For Pupils. First Series.* Supplements the above with material for slate work. Leatherette. 30 cts.

Badlam's Aids to Number. *For Teachers. Second Series.* Teachers' sight-work with objects above ten. 40 cts.

Badlam's Aids to Number. *For Pupils. Second Series.* Supplements above with material for slate work from 10 to 20. Leatherette. 30 cts.

Badlam's Number Chart. 11 x 14 inches. Designed to aid in teaching the four fundamental rules in lowest primary grades. 5 cts. each; per hundred $4.00.

Luddington's Picture Problems. 70 cards, 3 x 5 inches, in colors, to teach by pictures combinations from one to ten. 65 cts.

Pierce's Review Number Cards. Two cards, 7 x 9, for rapid work for second and third year pupils. 3 cts. each ; per hundred $2.40.

Howland's Drill Card. For rapid practice work in middle grades. 3 cts. each; per hundred $2.40.

For advanced work see our list of books in Mathematics.